The Potential Distribution of Chinese Mitten Crabs (*Eriocheir sinensis*) in Selected Waters of the Western United States with U.S. Bureau of Reclamation Facilities

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Tracy Fish Collection Facilities Studies
Volume 21

United States Department of the Interior
Bureau of Reclamation
Mid-Pacific Region and the Technical Service Center

November 2001

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Acknowledgments

We would like to thank Klaus Anger, James Athearn, Martin Attrill, Mark Buettner, Jose Ferrero-Rodriguez, Stephan Gollasch, Kathy Hieb, Leslie Hanna, Lloyd Hess, Zach Hymanson, Debbie Rudnick, Scott Siegfried, Richard Tullis, Tanya Veldhuizen, Johnson Wang and Kim Webb for providing us with information, answering our numerous questions, or reviewing the manuscript. We are especially grateful to Nai-Gang Zhao for granting us an interview, Tanya Veldhuizen for arranging it and Johnson Wang for translating; to James Athearn for his extensive help with the Columbia River section; and to Debbie Rudnick and Lloyd Hess for their detailed and perceptive comments on the manuscript. Given our shamefully limited language skills, we are indebted to Nicole David, Rainer Hoenicke, Marilyn Myers, Erin Sauls and Johnson Wang for providing translations or assistance with translations of various Chinese, German, Danish and French writings on mitten crabs, whether done for us or for others. We thank Pat Chambers and Michael May for assistance with the maps; Cristina Grosso for text scanning and transcription; Charles Liston and Diana Weigmann for their patient support as project managers; and Jack Laws for allowing us to reproduce his mitten crab drawing on the cover.

Life History of the Chinese Mitten Crab *Eriocheir Sinensis*

The Chinese mitten crab (Order Decapoda, Family Grapsidae) is native to China and Korea and has been introduced to Europe and North America. It reaches an adult size of about 30-90 mm in carapace width, with a gray-green or greenish-brown dorsal surface and a white ventral surface. Larger juveniles and adults have a dense mat of brown, hair-like setae on the front claws, a feature distinctive to the genus *Eriocheir.*

Mitten crabs are catadromous, living most of their lives in fresh or brackish water and migrating to brackish or salt water to reproduce. The seasons and locations where the various life stages of the mitten crab are found are sumarized in Table 1. After 1-4 years in fresh or brackish water, where the crabs feed on aquatic vegetation and benthic invertebrates,[1] their gonads begin developing during the summer and the crabs move downstream into brackish or salt water in late summer to early fall, where mating takes place. Anger (1990) suggested that downstream migration is probably triggered by hormones from the developing gonads, but other researchers reported that in China migration is triggered by a drop in water temperature from 25°C to 20°C (Jin & Li 1998; Hymanson *et al.* 1999; Zhao presentation 1999; Veldhuizen 2000), Siegfried (1999) reported that in California the start of peak downstream migration coincided with the onset of cooler water temperatures,[2] and Vincent (1996) argued that in France and Germany downstream migration correlated with increasing river flows. Copulation is initiated in brackish water. Each female produces up to 250,000 to 1,000,000 eggs, which she carries

Table 1. Timing and location of mitten crab life stages

Life Stage	Period	Location	References
Gonad Development	summer-late fall	river	Hoestland 1948; Veldhuizen & Stanish 1999
Downstream Migration	late summer-early winter	river to estuary	Panning 1939; Hoestland 1959; Cohen & Carlton 1997; Veldhuizen & Stanish 1999; Hymanson *et al.* 1999
Mating and Egg Extrusion (Spawning)	late fall-winter	estuary	Panning 1939; Anger 1990; Veldhuizen & Stanish 1999; Hymanson *et al.* 1999
Embryonic Development	late fall-summer	estuary	Peters 1933; Veldhuizen & Stanish 1999; Rudnick et al. 1999
Hatching	late winter-summer	estuary	Panning 1939; Anger 1991; Cohen & Carlton 1997; Veldhuizen & Stanish 1999; Hymanson *et al.* 1999
Larval Development	spring-fall	estuary	Peters 1933; Hoestland 1959
Settlement	sring-fall	estuary	Cohen & Carlton 1997; Hymanson *et al.* 1999; Rudnick pers. comm. 2001
Upstream Migration	some migration all year, but mainly late winter-summer	estuary to river	Panning 1939; Veldhuizen & Stanish 1999; Hymanson *et al.* 1999

1 We found no evidence that mitten crabs eat live fish, except as they may find injured fish or fish that are caught and disabled in nets or traps (e.g. Elton 1936). Other than in such circumstances (crabs and fish caught together in traps), fish apparently never account for a significant part of the mitten crab's diet. When kept together in aquariums, crabs do not catch healthy fish (Hess pers. comm. 2001).

2 However, according to Siegfried's (1999) Figures 1 and 2, the number of downstream migrating crabs in 1997 began to rise 12 days after a drop in temperature from 23°C to 21.5*C and 5-8 days before the start of a further drop to 15°C, and and in 1998 rbegan to rise 4 days before and continued to rise until 5 days after the start of a slow (≈50 day) drop in temperature from 24°C to 12°C.

attached to hairs on the pleopods on the underside of her abdomen. The eggs take 1-2 months to hatch, which mainly occurs in spring or early summer. The adults usually die soon thereafter, although Peters (1938) found that in the laboratory a few females may live to successfully spawn twice in a season, and concluded from field evidence that a small percentage of females survive spawning to reproduce again in the following year. During 1-2 months in the plankton,[3] the larvae develop through five zoeal stages and one megalops stage, and settle to the bottom mainly in summer or fall. Upstream migration may begin in the megalops stage (reportedly traveling as much as 20 km per day in China), and continues with settled crabs crawling along the bottom. Although some upstream migration apparently takes place in all months of the year in some rivers, most of it occurs in the spring and summer. Mitten crabs have been reported as far upstream as 700 km up the Elbe River at Prague, and 1400 km up the Yangtze River (Peters 1933; Panning 1939; Hoestland 1948; Ingle 1986; Anger 1990, 1991; Cohen & Carlton 1997; Hymanson *et al.* 1999; Zhao presentation 1999).

Two types of Chinese mitten crabs have been reported in China. The first type ("large river" type) spends two or more years in freshwater, ascending the river from a few to nearly 1,000 km, before maturing. It grows to a large size (typically 100-500 g), is generally found in large river systems, and is the type that is harvested and marketed. The second type ("coastal stream" type) is typically found in small coastal streams where it remains near the coast and matures in one year or less. It grows to a maximum size (≤100 g) that is too small to market (Zhao presentation 1999; Zhao pers. comm. 1999; Veldhuizen 2000). It is unclear whether these distinctions in behavior, lifespan and size are due to differences in genetics or environment. Zhao (pers. comm. 1999) reported that transplants of large commercial crabs from the Yangtze River to waters near Hong Kong resulted in the establishment of a population of small crabs that were unsuitable for marketing, suggesting that the differences are due to environmental conditions. On the other hand, Li *et al.* (1993) reported that these transplants produced "a good fishery resource" consisting of crabs that were smaller than those in the Yangtze but larger than the crabs historically identified as *Eriocheir japonicus* that are native to the region. Hybridization between the transplanted and native crabs could be an explanation for the intermediate-sized crabs (see discussion below under Taxonomic Treatment). It is also reported that mitten crab megalopae are sometimes harvested from small coastal streams and sold to crab culturers (being misrepresented as larvae of the "large river" type of crab from the Yangtze River), and these crabs do not grow large enough to market (Zhao pers. comm. 1999), suporting the idea that the differences are genetic. Zhao (Zhao presentation 1999; Veldhuizen 2000) suggested that both types of mitten crab are present in California, the "coastal stream" type in the small streams entering South San Francisco Bay, the "large river" type in the Sacramento-San Joaquin River system.

The highest densities of mitten crabs occur within the estuaries and lower portions of rivers, but high densities of mitten crabs have been reported as far as 90 km upstream of the mouth of the Thames River (Attrill & Thomas 1996) and 450 km upstream of the mouth (about 350 km from the head of the estuary) in the Elbe River (Panning 1939). These densities can vary greatly over the years. It is reported that in China wild populations of mitten crabs fluctuated historically with drought or flood, though no population estimates are available (Hymanson *et al.* 1999). In the Yangtze river the wild population has declined to low numbers since the 1960s, perhaps due to loss of habitat, pollution and overharvesting (Hymanson *et al.* 1999). In the North Sea region of Europe, mitten crabs became extremely abundant in the late1920s and 1930s (about 20 years after

3 The duration of the larval stages varies with temperature and salinity. For example, Anger (1991) reported the mean duration of the five zoeal stages to range from 25 days at 18°C to 61 days at 12°C at a constant salinity of 25 ppt; and to range from 36 days at 32 ppt to 40 days at 20 ppt at a constant temperature of 15°C (estimated from Fig. 4 in Anger (1991)). The developmental periods of larvae spawned from San Francisco Bay mitten crabs and reared in the laboratory were generally consistent with these ranges (Tullis pers. comm. 2001).

their initial detection) and subsequently declined (Panning 1939; Attrill & Thomas 1996; Veldhuizen & Stanish 1999). Based on a survey of fishermen, waterway authorities and others, Gollasch (1999) reported that there were high densities of crabs in the Elbe, Havel and Weser rivers in Germany in 1930-39, with modest population resurgences in 1953-60, 1969-75 and 1979-83, and a major increase from 1993 to the present, possibly comparable in scale to that of the 1930s. Türkay (pers. comm. 1995) reviewed the available literature, information from fishery offices and data from field work, and found that crab populations in Germany increased in the 1980s after dramatically declining in previous decades. Mares (pers. comm. 1997, 1998; also Strandwerkgroep 2001) reported that in Belgium the mitten crab was abundant from the mid-1930s to the mid-1950s, then virtually disappeared until 1994, and was abundant again in 1996-97; and that in the Netherlands it was abundant in the 1930s-50s, with large numbers ("plagues") also occurring in 1942, 1949, 1953, 1954, 1977, 1978 and 1981-85. Wolff & Sandee (1971) reported that mitten crabs were common or abundant along the Netherlands coast, and Ingle (1986) referred to a "plague of mitten crabs" in the Netherlands in 1981. Mitten crabs were occasional in the Seine River estuary and common in the Gironde Estuary system in northern and southwestern France in the latter half of the 1950s (Hoestland 1959; Vincent 1996), and have since been rare in both systems (Crivelli pers. comm. 1995; Vincent 1996; Noel pers. comm. 1999); and were moderately abundant in the Tagus River in Portugal in 1988-90, and then declined (Cabral & Costa 1999). Mitten crabs were occasionally caught in the Thames River in southern England in the 1970s and 1980s (Andrews *et al.* 1982; Clark *et al.* 1998), and then became abundant and spread upstream beginning in 1992, following a three-year drought (Atrill & Thomas 1996). In the San Francisco Estuary, mitten crabs peaked in abundance in 1998 about five years after their initial detection (Veldhuizen & Stanish 1999).

Figures 1 and 2 illustrate a conceptual model of the establishment, growth and spread of mitten crabs as seen in Europe and the United States. In this model, mitten crabs are initially introduced to

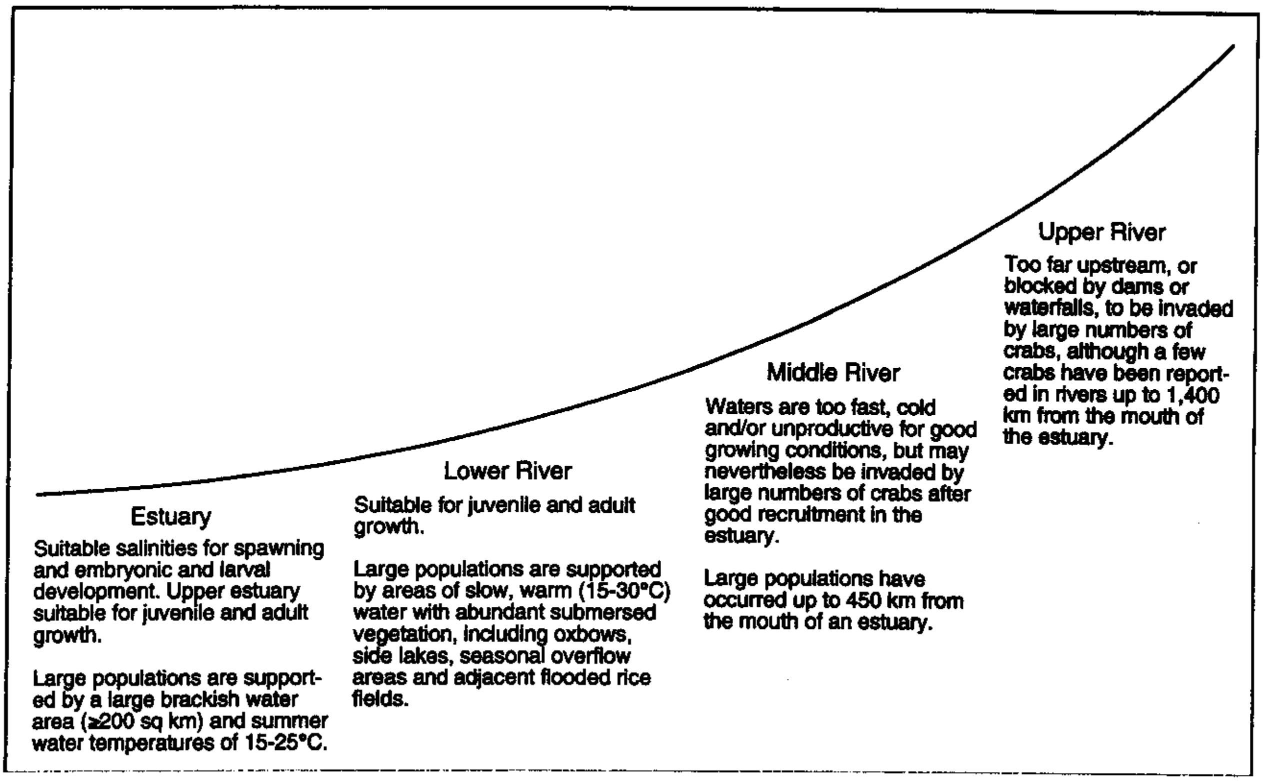

Figure 1. Mitten crab's use of estuary and river sections

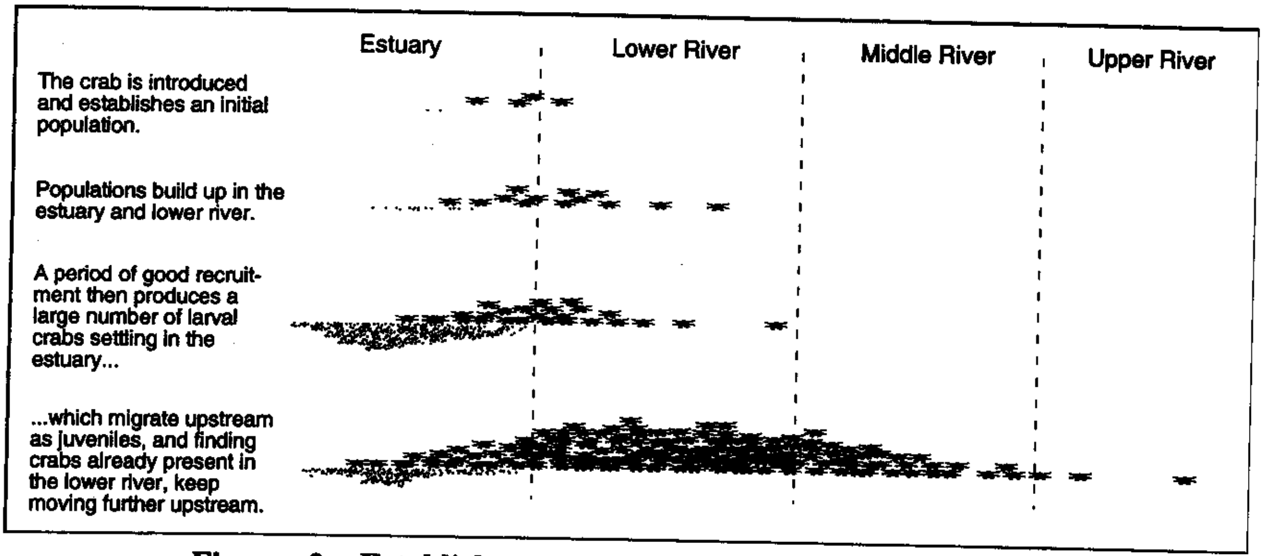

Figure 2. Establishment, growth and spread of a mitten crab population within a watershed

an area, become established, and slowly build up populations in the estuary and lower river until a period of favorable conditions (such as warm water temperatures) results in the successful recruitment of large numbers of juvenile crabs in the estuary. In the following spring and summer, competition for food and space forces many of these young crabs to migrate upstream past the lower river to middle and upper river areas (Ingle 1986; Fladung pers. comm. 1999; Zhao presentation 1999), resulting in a sudden "explosive" appearance of mitten crabs in these areas. In later years, the return of less favorable environmental conditions leads to poorer recruitment in the estuary, with few crabs migrating above the estuary and lower river. This model highlights three salient points: (1) "booms" in mitten crab populations are noted when large numbers of crabs move upstream into the river sytem; (2) after the initial introduction, it takes some years of population growth in the estuary and lower river before a large upstream migration can be launched; and (3) the pattern of subsequent boom and bust is governed primarily by conditions in the estuary and lower river.

Taxonomic Treatment of the Genus *Eriocheir*

Workers traditionally recognized four species of *Eriocheir*: *E. sinensis* H. Milne Edwards 1853, distributed from the central China coast around Fujian province (spelled as Fukien or Fokien in earlier writings) to the west coast of the Korean peninsula; *E. japonicus* de Haan 1835, from southern China, eastern Taiwan, Japan and the east coast of Korea, and reported recently (Zhao pers. comm. 1999) from the Yangtze River; *E. leptognathus* Rathbun 1914, from Fujian province to the west coast of Korea; and *E. rectus* Stimpson 1858, from near Macao and western Taiwan (Tesch 1918; Sakai 1939, 1976; Dai 1988; Dai & Yang 1991; Hymanson *et al.* 1999). Despite some difficulties in distinguishing *E. sinensis* and *E. japonicus* in some regions (e.g. Panning 1938), they nevertheless were long considered to be good species; and we found that adult specimens that had been identified as *E. sinensis* (from Germany and California) and *E. japonicus* (from Japan) were readily distinguished by clear and consistent morphological differences as described by Tesch (1918), Sakai (1939, 1976), and Dai & Yang (1991). Some recent work, however, has argued for various modifications of this scheme.

Dai (1991) distinguished two subspecies of *E. japonicus*: *E. j. japonicus* from Japan, eastern Korea, Taiwan, and southern China around Hong Kong, and *E. j. hepuensis* further south in

China on the Nanliu River, at Hepu in Guangxi province. Li *et al.* (1993), conducting morphological and allozyme electrophoresis analyses of crabs from the Yangtze River (within the reported native range of *E. sinensis*) and from three areas near Hong Kong (within the reported native range of *E. japonicus*), found small genetic distances between these populations and synonymized *E. sinensis* under *E. japonicus*, despite finding morphological differences. Their analysis may be compromised by the fact that two of the sampled watersheds near Hong Kong had received several transplants of mitten crabs from the Yangtze River (and therefore presumably consisting of *E. sinensis*) over the preceding two decades. Li *et al.* (1993) explained the morphological differences as probably being ecophenotypic, but from the data they present the differences seem as likely to be genetically based, with the intermediate morphologies in the two watersheds that had received transplanted crabs possibly resulting from hybridization.

Chan *et al.* (1995) synonymized *E. recta* that had been reported from Macao (Stimpson's 1858 type description) under *E. japonicus*, and described a new species, *E. formosa*, for crabs from eastern Taiwan that had previously been identified as *E. recta*. They described the conclusions of Dai (1991) and Li *et al.* (1993) as "premature." Guo *et al.* (1997), based on detailed morphological examination of a large series of crabs, argued for five species of mitten crabs: three to remain in the genus *Eriocheir—E. sinensis*, *E. japonicus* and *E. hepuensis*, the latter being raised from subspecies status—and two that they argued appeared distinct enough to each warrant its own momotypic genus—*E. leptognathus* (which Sakai (1983) had placed in a new genus, *Neoeriocheir*, but which subsequent authors had rejected) and *E. formosa*. They also reported that Xie (1996) had found *E. sinensis* and *E. hepuensis* to be clearly distinguished by RAPD analyses of nucleic DNA, and argued that, contrary to a few reports in the literature, there was no clear evidence of hybridization occurring between *E. sinensis* and *E. japonicus*.

Montú *et al.* (1996) reared and described the complete larval series in *E. sinensis* and compared it with the published description of *E. japonicus* larvae, and found enough differences to consider them separate species. Ng *et al.* (1998), reared and described *E. hepuensis* larvae and compared them to the published descriptions of the larvae of the other four nominal *Eriocheir* species. They found *E. sinensis*, *E. japonicus* and *E. hepuensis* larvae to be closely similar but distinguishable; and *E. leptognathus* and *E. formosa* larvae to be more easily distinguished from the group of three species and from each other, consistent with the taxonomic revisions suggested by Guo *et al.* (1997). Ng *et al.* (1999) then formally reassigned *E. leptognathus* to the genus *Neoeriocheir*, and *E. formosa* to a new genus, *Platyeriocheir*, based on ontogenic and adult morphological differences.Finally, Tsukimura and Toste (2000) found that under denaturing conditions the yolk protein vitellin consisted of four subunits in *E. sinensis* in contrast to the two subunits reported for *E. japonicus*.

Although we suspect the taxonomy of this group of crabs is not yet settled, at this time we feel comfortable in continuing to treat *E. sinensis* as a species distinct from *E. japonicus*. In this report, "mitten crab" will refer to the Chinese mitten crab, *E. sinensis*, unless otherwise stated.

Methods for Estimating Potential Range

Potential ranges have been estimated for several nonindigenous marine and freshwater organisms based primarily on physical and chemical characteristics of the environment. In these studies threshold values for these factors have been estimated from the organism's existing distribution, from observations of annual or seasonal changes in its distribution, from laboratory experiments on environmental tolerances and on growth or developmental responses to changes in environmental characteristics, and from field observations indicative of such tolerances and responses. For example, the potential ranges of zebra mussels, *Dreissena polymorpha*, in various regions of North America have been estimated based upon air temperature, water temperature, salinity or conductivity, calcium concentration, dissolved oxygen concentration, pH and water transparency (Strayer 1991; Neary & Leach 1992; Murray *et al.* 1993; Baker *et al.* 1994; Doll 1997; Hayward & Estevez 1997; Sorba & Williamson 1997; Cohen & Weinstein 1998), with the threshold values for these estimates based on a large set of distributional, laboratory/experimental and field/observational data (O'Neill 1996; Cohen & Weinstein 2001 and references therein). Similarly, the world-wide potential range of the European green crab, *Carcinus maenas*, has been estimated based upon evidence regarding its summer and winter temperature limits (Carlton & Cohen 2001); and the potential northern range limits in United States territory of the Mediterranean clone of the tropical green seaweed *Caulerpa taxifolia* were estimated based on its observed distribution relative to temperature in the Mediterranean Sea (Cohen *et al.* 1998).

The basic environmental threshold approach assumes that different environmental characteristics act independently upon distribution, and thus misses synergistic effects. Such effects may be common. For example, zebra mussels can tolerate a lower pH at higher calcium concentrations (Ramcharan *et al.* 1992), and mitten crab larvae can tolerate a broader range of salinities at higher temperatures (Anger 1991; see below). Modifications of the threshold approach may address this problem to some degree (e.g. Cohen & Weinstein 1998 included adjustments that recognized synergies between calcium and pH), but a more direct approach is to utilize regressions of existing distribution (presence/absence) on two or more environmental factors, as has been done for zebra mussels (Ramcharan *et al.* 1992; Koutnik & Padilla 1994; Hincks & Mackie 1997). Where sufficient data is available, and within the range of environmental values used to produce the regressions, this method may provide a more accurate delineation of distributional boundaries than would a simple threshold approach. However, the results obtained outside of those values may be less reliable (Weinstein & Cohen 2001).

Aside from the complications introduced by synergies between environmental factors, estimates by any method may underestimate potential range if:

- unrecognized confounding factors in experiments limit the survival, growth or development of the organism rather than the factors under investigation; or
- unrecognized confounding factors—including biological factors such as competition, predation, parasites or disease; or barriers to migration—control the observed distribution of the organism in the environment rather than the factors under investigation.

Potential range may be overestimated if:

- experiments are not conducted on the most sensitive life stage relative to the factor being investigated;
- deductions based upon distributional data mistakenly assume that transient populations are permanent, or that populations that result from ongoing recruitment from distant populations are reproducing and recruiting locally; or
- untested factors—such as the biological factors listed above—control the distribution of the organism in the invaded environment.

In this study, we used an environmental threshold approach to estimate the potential distribution of mitten crabs into river systems in the western United States with U.S. Bureau of Reclamation (USBR) facilities, comparing the environmental requirements and limits of mitten crabs with environmental conditions in these areas. This threshold approach was augmented with an assessment of factors affecting mitten crab abundance, and factors restricting mitten crab migration within a river system. We identified the distribution of mitten crabs and assessed environmental requirements and migratory barriers for mitten crabs through a review of the peer-reviewed scientific literature, "gray" literature, and unpublished data and observations provided by workers in China, Europe and the United States. Data on environmental conditions and USBR facilities were obtained from the literature and from workers in government agencies, and in academic and other institutions.

Global Distribution of Chinese Mitten Crabs

The Chinese mitten crab *Eriocheir sinensis* is native to coastal streams and rivers in China and Korea from latitudes of 24-42°N,[4] including parts of the south China Sea, East China Sea and Yellow Sea, from Fujian province in China to the Yalu River in South Korea (Sakai 1939; Panning 1939; Hymanson *et al.* 1999; Zhao presentation 1999). "Population centers" of mitten crabs are found in three or four large rivers in China: Zhao (pers. comm. 1999) reports the Liao, Yangtze and Oujiang rivers as main population centers; Jin & Li (1998) additionally list the Hai River. Mitten crabs from the Yangtze River were repeatedly introduced to waters near Hong Kong in the 1970s-90s, in latitudes of 22-23°N, with uncertain results.[5]

The first mitten crab collected in Europe was found in Germany in a tributary of the Weser River in 1912. Since then, mitten crabs have become extremely abundant at times in coastal plain rivers and estuaries on the North Sea coasts of Germany, Holland and Belgium, especially in the Elbe, Eems and Rhine river systems (Panning 1939; Hoestland 1948; Ingle 1986; Mares pers. comm. 1998; Gollasch 1999). They also spread into France and became moderately abundant in the Gironde Estuary watershed during the 1950s, (Hoestland 1959). They spread up the Dordogne and Garonne rivers in 1953-58 (Hoestland 1959), and were collected in the Languedoc lagoons on France's Mediterranean coast in 1959-68 after apparently passing through the Midi Canal (Petit 1960; Petit & Mizoule 1974), but did not establish breeding populations in the Mediterranean (Petit & Mizoule 1974; Noel pers. comm. 1999). Two mitten crabs have been collected in the Black Sea, one in the late 1990s and one in 2000 (Zaitsev pers. comm.; Gollasch pers. comm. 2001). Mitten crabs became moderately abundant in the Tagus River in Portugal in 1988-90 (Cabral & Costa 1999), and have been established in the Guadalquivir River on the Atlantic coast of southwestern Spain since 1999 or 2000 (Ferrero-Rodriguez pers. comm. 2001). In England, they became moderately abundant in the Thames River in England starting in 1992 (Atrill & Thomas 1996; Clark *et al.* 1998); while further to the north one mitten crab was collected in the Humber River drainage in England in 1949, with occasional crabs seen there since 1976 (Clark 1984; Ingle 1986; Hemsley-Flint pers. comm. 1999). Adult mitten crabs have also been collected throughout the Baltic Sea, but have apparently not established breeding populations in these areas (Haahtela 1963; see discussion below). Two mitten crabs collected near Oslo in Norway are the northernmost records in the North Sea (around 59.5°N), but mitten crabs are apparently not established there (Christiansen 1977, 1988). Mitten crabs have become established in Europe at latitudes of up to 54°N, exceeding the northernmost distribution of crabs in their native range by 12°.

In North America, mitten crabs have become established and abundant in the Sacramento-San Joaquin River watershed (San Francisco Bay watershed) in California since 1992 (Cohen & Carlton 1997; Rudnick *et al.* 1999, 2000). Twelve to fourteen adult mitten crabs (two reports not

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4 The latitudes given in this report are the approximate latitudes of the estuary mouths of the watersheds under consideration. In some cases, the inland portions of the watersheds may extend considerably to the north or south of these latitudes.

5 Mitten crabs from the Yangtze River were introduced as megalopae or seed crabs at sites near Hong Kong on several occasions since the 1970s, including numerous releases into the Zhujiang River (Pearl River) and two releases (in 1983 and 1984) into a stream at Yantian (Li *et al.* 1993; Guo *et al.* 1997; Zhao pers. comm. 1999). According to Zhao (pers. comm. 1999), these crabs became established at least temporarily, but matured quickly at small size (as small as ≤50 g), and were a commercial failure. Li *et al.* (1993), on the other hand, reported that "a good fishery resource was established within a few years" in the lower Zhujiang River, though the crabs were smaller than those from the Yangtze River. An effort to raise mitten crabs commercially in Taiwan also failed (Zhao presentation 1999), although it is unclear whether the report of failure means that the crabs did not grow large enough to be commercially useful or that they failed to become established. Zhao (presentation 1999, pers. comm. 1999) attributed both failures to high water temperatures. Hymanson *et al.* (1999) reported that mitten crabs had been successfully introduced into Vietnam, but Zhao (pers. comm. 1999) stated that he was unaware of any introduction into Vietnam.

confirmed) were collected in the Great Lakes from 1965 to 1997 (Nepszy & Leach 1973; Hemdal pers. comm. 1997; Niimi pers. comm. 2001), all of them thought to be individuals that arrived directly from overseas, with no reproduction occurring in the lakes. A single Chinese mitten crab was collected in Louisiana at Bay Gardene in the Mississippi River delta in 1987 (Felder pers. comm. 1995). A large, male Japanese mitten crab (*Eriocheir japonicus*) was caught in the lower Columbia River near Chinook in 1997 (Dumbauld pers. comm. 2001). A report of another mitten crab caught in the Columbia River near Portland in 1999 remains unconfirmed (Sytsma pers. comm. 2001). Reports that a mitten crab had been collected in Hawaii in the 1950s (Gollasch 1997; Veldhuizen & Stanish 1999) are in error (Gollasch pers. comm. 2001).

Mitten crabs tend to become abundant in large estuary and river systems. Table 2 provides some information on the systems where mitten crabs have been reported as abundant.

Table 2. Characteristics of watersheds with large mitten crab populations
IN ASIA
Liao River, China (also as Liao He) *Latitude at mouth:* 41°N *Estuary Description:* low gradient river and estuary lie in the flat, swampy Liao Plain (Encyclopedia Britannica 1994) *Sea Surface Temperature:* Feb: ≤0°C; Aug: 23-24°C (Sverdrup *et al.* 1942) *River Size and Flow:* 1,345 km long; 215,000 km^2 watershed (Encyclopedia Britannica 1994); mean discharge of 1,180 m^3/s (Hydropower 2001)
Hai River, China (also as Hai He, Hai Ho) *Latitude at mouth:* 39°N *Estuary Description:* low gradient river and estuary lie in the flat Hopeh Plain (Encyclopedia Britannica 1994) *Sea Surface Temperature:* Feb: 0°C; Aug: 24°C (Sverdrup *et al.* 1942) *River Size and Flow:* 208,500 km^2 watershed; large seasonal variation in flow, low in winter, high in summer and fall, with frequent floods until water control project began operation in 1963 (Encyclopedia Britannica 1994); mean discharge of 1,280 m^3/s (Hydropower 2001)
Yangtze River, China (also as Yangtse, Yangzi, Chang Chiang, Chang Jiang) *Latitude at mouth:* 31.5°N *Estuary Description:* tidal influence extends to 400 km from mouth (Encyclopedia Britannica 1994); estuary is over 15 km wide and about 6 m deep (Gao 2001); brackish area at mouth of river covers 12,000 km^2 (Zhao pers. comm. 1999); lower river and estuary lie at southern edge of the North China Plain; many large side lakes along lower river with total area of over 17,000 km^2; 4-5 m tides near mouth; river annually carries 280-300 million tons of sediment to its mouth (Encyclopedia Britannica 1994) *Sea Surface Temperature:* Feb: 8-10°C; Aug: 26-27°C (Sverdrup *et al.* 1942); Jan: 13°C; Jul: 25°C (NOAA 1999) *River Size and Flow:* 3rd longest river in the world, and 4th largest in volume; 6,300 km long; 1,959,000 km^2 watershed; mean discharge of 34,000 m^3/s, range of discharge from low flows of 6,000-8,000 to peak flows of 50,000-70,000 m^3/s; floods begin in Mar-Apr with monsoon rains and usually last 8 months, with highest water in August (Encyclopedia Britannica 1994); lower reach is 930 km long with a gradient of 0.005 m/km (Gao 2001)
Oujiang River (also as Ao River), **China** *Latitude at mouth:* 28°N *Sea Surface Temperature:* Feb: 10-13°C; Aug: 26-27°C (Sverdrup *et al.* 1942); Jan: 18°C; Jul: 27°C (NOAA 1999)

IN EUROPE

Elbe and Havel rivers, Germany

Latitude at mouth: 54°N

Estuary Description: 90 km long (Encyclopedia Britannica 1994); 140 km long to upstream boundary of tides at the dam at Geeshacht (Peitsch 1995); salinity gradient reaches to 55 km from mouth, turbidity maximum is between 25 and 60 km from mouth (Peitsch 1995); estuary covers 900 km^2 in North German Plain, with extensive tidal flats and sand banks; turbid; steep longitudinal salinity gradient; turbidity maximum 40 km from mouth; residence time of 13 days; maximum tidal currents of 2.3 m/s (Encyclopedia Britannica 1994;Goosen *et al.* 1995; Peitsch 1995; Fladung pers. comm. 1999)

Sea Surface Temperature: Feb: 3°C; Aug: 17-18°C (Sverdrup *et al.* 1942); Jan: 5-7°C; Jul: 15-16°C (NOAA 1999)

Estuary Temperature: 6°C in Mar 1992, 35 km from mouth (Goosen *et al.* 1995); 8-16°C in Apr/Jun 1989, 18.5°C in Aug: 1989

River Size and Flow: 1,165 km long with 144,060 km^2 watershed, and mean discharge of 710 m^3/s (Encyclopedia Britannica 1994); 1,143 km long with mean discharge of 700 m^3/s (Peitsch 1995); 146,500 km^2 watershed (Goosen *et al.* 1995); discharge of 1600 m^3/s measured in Mar 1992 (Goosen *et al.* 1995); velocity of 0.1-1.5 m/s (Fladung pers. comm. 1999)

Weser River, Germany

Latitude at mouth: 53.5°N

Estuary Description: mean depth of 9-15 m, mean tide range of 3.8 m at Bemerhavenand 4.0 m at head of tides 72 km upstream at Bremen Dam; sediment discharge of 10-310 kg/s; turbidity maximum develops in region with salinity of 2-5 ppt, with turbidity ≤0.5 kg/m^3 elsewhere (Encyclopedia Britannica 1994; Tomczak 2000; Zimmermann *et al.* 2000; Clout 2001)

Sea Surface Temperature: Feb: 3°C; Aug: 17-18°C (Sverdrup *et al.* 1942)

River Size and Flow: 700 km long to river mouth at Bremerhaven; 135 km above Bremen has been straightened and is navigable by large ships; 38,000 km^2 watershed; mean discharge of 320m^3/s, range of 120-1,200 m^3/s (Encyclopedia Britannica 1994; Zimmermann *et al.* 2000; Clout 2001)

Eems River and Eems-Dollard Estuary, The Netherlands and Germany

Latitude at mouth: 53.5°N

Estuary Description: about 33 km long (Mees *et al.* 1995); covers 255 km^2, including 37 km^2 of freshwater tidal area (Mees *et al.* 1995); covers 500 km^2, of which 36% is intertidal (Sautour & Castel 1995); mean depth of 3.5 m in middle part of estuary; upper part, called the Dollard, has mean depth of 1.2 m and is 85% intertidal; maximum current velocity of 1.5 m/s; tidal excursion of about 15 km; residence time of 18-36 days; well-mixed except in Dollard where there is occasional stratification; turbidity of 0.1-0.4 g/l in maximum turbidity zone in oligohaline region; dissolved oxygen rarely below 70% saturation (Soetaert *et al.* 1995; Sautour & Castel 1995; Mees *et al.* 1995)

Sea Surface Temperature: Feb: 3-4°C; Aug: 17°C (Sverdrup *et al.* 1942); Jan: 5-7°C; Jul: 15-16°C (NOAA 1999)

Estuary Temperature: 19-21°C in summer 1991, from mouth to 50 km upstream (Mees *et al.* 1995)

River Size and Flow: 371 km long (Encyclopedia Britannica 1994); Eems has 12,650 km^2 watershed; discharge, including Westerwoldsche Aa river, ranges about 30-420 m^3/s (Mees *et al.* 1995); mean annual discharge of 80-180 m^3/s (Soetaert *et al.* 1995); mean annual discharge of 125 m^3/s from Ems plus ≈13 m^3/s from Westerwoldsche Aa (Sautour & Castel 1995)

Rhine River, The Netherlands and Germany

Latitude at mouth: 52°N

Sea Surface Temperature: Feb: 4-5°C; Aug: 17-18°C (Sverdrup *et al.* 1942); Jan: 5-7°C; Jul: 15-16°C (NOAA 1999)

River Size and Flow: 1,390 km long; navigable from its mouth to Basel, about 800 km; 220,000 km^2 watershed (Encyclopedia Britannica 1994)

Scheldt River and Westerscheldt Estuary, The Netherlands and Belgium

Latitude at mouth: 51.5°N

Estuary Description: covers 310 km^2, including 63 km^2 intertidal and 32 km^2 saltmarsh (De Jong & de Jonge 1995); covers 600 km^2, with 110 km^2 of tidal flats and marshes; has 70 km long marine zone, 50 km long central zone, and a tidal freshwater zone (Sautour & Castel 1995); covers about 300 km^2; 80 km long, with tides reaching to dam at Ghent, 160 km from mouth (Mees *et al.* 1995); stable turbidity maximum about 70 km from mouth, with turbity up to 0.1 g/l (but Mees *et al.* 1995 say there is no real turbidity maximum, with turbidity never above 0.05 g/l); residence time of 50-70 days; vertical salinity stratification weak (upstream) or absent (downstream); tide range of 2-5 m; tidal exchange of about 100,000 m^3/s; maximum currents in brackish zone of 1.65 m/s; river is heavily polluted from municipal and industrial discharge and stock-farming; tidal freshwater portion of estuary has high dissolved nitrogen levels and is frequently suboxic to anoxic conditions (Goosen *et al.* 1995; Middleburg *et al.* 1995; Escaravage & Soetaert 1995; Soetaert *et al.* 1995; Sautour & Castel 1995; Mees *et al.* 1995); salinity extends ≈100 km and tides ≈150 km from mouth; lower 102 km has surface area of 259 km^2; residence time is about 50 days in winter and about 70 days in summer in upper part of estuary, and 10-15 days in lower part (Soetaert & Herman 1995)

Sea Surface Temperature: Feb: 5°C; Aug: 17-18°C (Sverdrup *et al.* 1942); Jan: 5-7°C; Jul: 15-16°C (NOAA 1999)

Estuary Temperature: 10°C in Apr 1992, 50 km from mouth (Goosen *et al.* 1995); 20-23°C in summer 1991 (Mees *et al.* 1995)

River Size and Flow: 435 km long (Encyclopedia Britannica 1994); 330 km long (Middleburg *et al.* 1995); 19,500 km^2 watershed (Goosen *et al.* 1995); 20,000 km^2 watershed (Mees *et al.* 1995); mean annual discharge of about 100 m^3/s (Middleburg *et al.* 1995; Soetaert *et al.* 1995; Mees *et al.* 1995; Soetaert & Herman 1995); mean annual discharge about 105 m^3/s (Sautour & Castel 1995); discharge varies seasonally from 50 to 200 m^3/s (Escaravage & Soetaert 1995); discharge ranges 30-500 m^3/s (Mees *et al.* 1995)

Thames River, England

Latitude at mouth: 51.5°N

Estuary Description: 110 km long (Attrill & Thomas 1996); tidal for 65 km (Encyclopedia Britannica 1994); covers 275 km^2 (estimated from map in Andrews *et al.* 1982)

Sea Surface Temperature: Feb: 5-7°C; Aug: 16-17°C (Sverdrup *et al.* 1942); Jan: 5-7°C; Jul: 15-16°C (NOAA 1999)

Estuary Temperature: 5-10°C in winter; 17-23°C in summer in 1977-1992, 60 km from mouth; temperatures are lower in the river, with a minimum below 5°C (Attrill & Thomas 1996)

River Size and Flow: 338 km long (Encyclopedia Britannica 1994); discharge of 30-350 m^3/s (Attrill & Thomas 1996); peak flows of about 50 m^3/s in the 1990s (Clark *et al.* 1998)

Gironde Estuary and Garonne and Dordogne rivers, France

Latitude at mouth: 45.5°N

Estuary Description: 45 km long (Encyclopedia Britannica 1994); 70 km long, with tides reaching 160 km upstream; 625 km^2 at high water, with 50 km^2 intertidal (Castel 1995; Sautour & Castel 1995; Mees *et al.* 1995); mean depth of 5-19 m; "salt wedge-type" or "slightly stratified" at high flow, partially mixed at low flow; residence time of 20-86 days; salinity intrusion to 40 km from inlet at high flow, 75 km at low flow; tidal currents up to 2.5 m/s during spring tide ebb; residual circulation with turbidity maximum at upper limit of salinity intrusion; highly turbid, receiving 1.5-3 million tons/yr of suspended sediment, with turbidity typically >0.5 g/l and sometimes >1 g/l over much of the estuary, and up to 10 g/l near the bottom (Castel 1993, 1995; Sautor & Castel 1995); generally well-mixed, with virtually no stratification in summer; residence times average 10 days in winter and 70 days in summer (Mees *et al.* 1995)

Sea Surface Temperature: Feb: 10°C; Aug: 19°C (Sverdrup *et al.* 1942); Jan: 11°C; Jul: 16-19°C (NOAA 1999)

Estuary Temperature: Feb: 8°C, Jun-Aug: 20-23°C, monthly averages for 1978-1992 (Castel 1995); 21-24°C in summer 1991 (Mees *et al.* 1995)

River Size and Flow: Garonne River is 620 km long with a 56,000 km^2 watershed (Encyclopedia Britannica 1994); estuary has a 71,000 km^2 watershed with a mean annual discharge of 800-1,000 m^3/s, with monthly mean discharge ranging from around 250 to 3,000 m^3/s during 1978-1992 (Castel 1993, 1995); mean discharge of 600-1,000 m^3/s (Soetaert *et al.* 1995); mean annual discharge of 900 m^3/s (Sautour & Castel 1995); discharge varies 200-1,500 m^3/s, on average 800-1,000 m^3/s (Mees *et al.* 1995)

Tagus River, Portugal
Latitude at mouth: 39°N
Estuary Description: about 40 km long; covers 320 km^2, of which 37% is intertidal (Moreira *et al.* 1992); extensive intertidal mud and sandy/mud flats and saltmarsh, covering >30% of estuary; high turbidity (Moreira *et al.* 1992; Soetaert *et al.* 1995)
Sea Surface Temperature: Feb: 14°C; Aug: 19°C (Sverdrup *et al.* 1942); Jan: 13-16°C; Jul: 18-19°C (NOAA 1999)
Estuary Temperature: measured 14-15°C in winter, 23-25°C in summer, in 1995-96 (Cabral & Costa 1999)
River Size and Flow: 1,007 km long; 81,600 km^2 watershed (Encyclopedia Britannica 1994); discharge of 30-18,000 m^3/s (Soetaert *et al.* 1995)
IN NORTH AMERICA
Sacramento-San Joaquin rivers and San Francisco Bay Estuary, California
Estuary Description: covers 1,240 km^2, including 200 km^2 of mudflats (Conomos 1979); covers 1,410-1,520 km^2 (Monroe & Kelly 1992); covers 1,340 km^2 (NOAA 1998); covers about 1,450 km^2 (Cohen 2000); extensive intertidal, marsh and slough habitat; average depth of 6.3 m and volume of 8.4 km^3 at mid-tide; tidal prism of 1.6 km^3; mixed, semi-diurnal tides with a range of 1.7 m at the mouth; maximum ebb currents at the mouth are 2.8 m/s, but more typical maxima are 0.6-0.9 m/s in the channels and 0.35 m/s in the shoals, with a tidal excursion of about 10 km; 163,000 km^2 watershed (Conomos 1979; NOAA 1998; Cohen 2000)
Sea Surface Temperature: Feb: 11-12°C; Aug: 14-15°C (Sverdrup *et al.* 1942); Jan: 12-13°C; Jul: 14-16°C (NOAA 1999)
Estuary Temperature: 7-12°C in winter, 15-22°C in summer in San Francisco Bay (Conomos 1979); 7-27°C in Delta at Tracy in 2000-2001 (Craft *et al.* 2001); annual maximum in Delta of up to 31°C (Halat 1996)
River Size and Flow: 615 km long (Encyclopedia Britannica 1994); mean discharge into Delta of 600 m^3/s, total discharge into estuary of 660 m^3/s (Conomos 1979); mean discharge into Delta of 940 m^3/s, range over years of 230-2,700 m^3/s; total discharge into estuary of 1,050 m^3/s (Monroe & Kelly 1992); mean discharge into Delta of 920 m^3/s, total discharge into estuary of 1,050 m^3/s (NOAA 1998)
Note: Temperature data from Sverdrup *et al.* (1942) are estimated from isotherm charts.

Factors Affecting the Distribution and Abundance of Mitten Crabs

General Habitat Preference

Juvenile to adult stage mitten crabs prefer slow-moving, warm, shallow (to 2 m) waters with submerged vegetation (Panning 1939; Haahtela 1963; Jiang pers. comm. 1998; Hymanson *et al.* 1999; Zhao presentation 1999; Anger pers. comm. 1999). Fast-flowing, cold-water rivers have been thought to be unsuitable for rearing mitten crabs (Panning 1939; Hymanson *et al.* 1999). In China, abundant mitten crab populations are reared in vegetated, lacustrine habitats associated with the lower reaches of large rivers (Hymanson *et. al.* 1999). In coastal Korea, mitten crabs are often found in rice fields (Ingle & Andrews 1976). In Europe during the 1930s, the densest concentrations of mitten crabs developed in the low-lying portions of large river systems. These dense populations occupied less than about 10% of the crab's total European range (Panning 1939). In addition, because of the salinity range desirable during the 1-2 month, planktonic larval stage (see below), an estuary or coastal zone with a large brackish water area where larvae may be retained during their development is thought to be necessary to support large populations (Zhao pers. comm. 1999). In Asia, Europe and North America, watersheds that have supported large mitten crab populations have rivers that are over 300 km in length, drainage areas of more than 12,000 km^2, mean discharge of at least 100 m^3/s, and estuaries larger than 200 km^2 (Table 3).

Table 3. Summary of size and discharge data for watersheds that have supported large mitten crab populations

	Estuary Area (km²)	River Length (km)	Watershed Area (km²)	Discharge Mean (m³/s)	Discharge Range (m³/s)
Liao	–	1,345	215,000	1,180	–
Hai	–	–	208,500	1,280	–
Yangtze	12,000[a]	6,300	1,959,000	34,000	6,000-70,000
Oujiang	–	–	–	–	–
Elbe/Havel	900	1,143-1,165	146,500	700-710	1,600[b]
Weser	–	700	38,000	320	120-1,200
Eems/Dollard	255-500	371	12,650	80-180	30-420
Rhine	–	1,390	220,000	–	–
Scheldt	300-600	330-435	19,500	100-105	30-500
Thames	225	338	–	–	30-350
Gironde/Garonne/Dordogne	625	620	56,000	600-1,000	200-3,000[c]
Tagus	320	1,007	81,600	–	30-18,000
Sacramento/San Joaquin	1,240-1,520	615	163,000	≈1,000	≈300-3,000[d]

Data are summarized from Table 2.
a Estimated coastal area with ≤15 ppt salinity at mouth of river.
b Discharge for March 1992.
c Range of monthly means in 1978-1992.
d Range of annual means, 1921-1990.

We found no information on the occurrence of breeding populations in smaller coastal rivers in Europe. In China, populations of crabs are found in most small coastal streams and rivers (Jin pers. comm. 1998; Zhao presentation 1999). These populations are relatively small, and the crabs do not live as long nor grow as large as in the major population centers in the large river systems. As discussed above, it is unclear whether these size and lifespan differences are due to genetic differences between "coastal stream" and "large river" populations, or to environmental influences.

Summary: Breeding populations of mitten crabs occur in coastal systems ranging in size from small coastal streams to large rivers and estuaries. They become abundant in large river and estuary systems with extensive shallow areas with submerged vegetation.

Latitude

Factors that may affect distribution, such as coastal or river temperatures or productivity, can vary with latitude. The crab's native range in Asia extends from 24 to 42°N (Zhao pers. comm. 1999) and it may have become established as far south as latitudes 22-23°N (see discussion at Footnote 5). Watersheds that have supported large populations range from 28°N (Oujiang River, China) to 41°N (Liao River, China). In Europe, mitten crabs have established substantial populations in watersheds from 39°N (Tagus River, Portugal) to 54°N (Elbe River, Germany). They have been found as far north as 59.5°N in the North Sea and 66°N in the Baltic Sea, but do not appear to be established anywhere in Europe outside of 39-54°N.

Summary: Latitude does not directly affect mitten crabs, but important environmental factors such as temperature or productivity may vary with latitude. Substantial mitten crab populations have been observed at 28-41°N in Asia and 39-54°N in Europe.

Salinity

Mitten crabs can mature in fresh water, but require brackish or salt water for reproduction and development. The salinity requirements reported for mitten crabs vary with their life stage, as discussed here and summarized in Table 4. The available information includes some experimental data plus reports or assessments of salinity requirements that are based on field observations.

Table 4. Salinity ranges reported for mitten crabs

Life Stage	Possible Range	Optimal Range	Reference
Gonadal Development	0-? ppt	–	Hoestland 1948
	0-? ppt	–	Hymanson *et al.* 1999
Mating	6-31 ppt	–	Peters 1933, 1938
	15-27 ppt	–	Hoestland 1948
	–	10-16 ppt	Hymanson *et al.* 1999
	5-20 ppt	15-17 ppt	Zhao presentation 1999
Egg Adherence	–	above 25-30 ppt	Buhk 1938
	≥17 ppt	≥26 ppt	Peters 1938
	to 20 ppt or less	–	Anger pers. comm. 1999
	≥15 ppt	–	Zhao pers. comm. 1999
Embryonic Development	–	≥18 ppt	Peters 1938
	"need pure salt water"	–	Panning 1939
	8-33 ppt	–	Jiang pers. comm. 1998
	3-27 ppt	15-20 ppt	Zhao pers. comm. 1999
Hatching		≈23 ppt	Buhk 1938
Larval Development	–	16-17 ppt	Buhk 1938
	11-30 ppt	14-17 ppt	Peters 1938
	≥26 ppt	–	Rasmussen 1987
	8-33 ppt	13-26 ppt	Jiang pers. comm. 1998
	–	≈15 ppt	Zhao pers. comm. 1999
– to zoea I	10-32 ppt	15-25 ppt	Anger 1991[a]
– zoea I to zoea II	15-32 ppt	25-32 ppt	"
– zoea II to zoea III	15-32 ppt	20-32 ppt	"
– zoea III to zoea IV	15-32 ppt	15-32 ppt	"
– zoea IV to zoea V	15-32 ppt	25-32 ppt	"
– zoea V to megalopa	20-32 ppt	25 ppt	"
– megalopa to 1st juv	10-32 ppt	25 ppt	"
– late stage megalopa	0-? ppt	–	Zhao presentation 1999
Metamorphosis and Settlement	0-? ppt	–	Panning 1938
	10-32 ppt	25-32 ppt	Anger 1991[a]

[a] Data from Anger 1991 are from experiments conducted at 15°C and salinities of 10-32 ppt, so that limits below 10 or above 32 ppt could not be detected.

Gonadal development. The gonads begin development in freshwater (Hoestland 1948) and may possibly complete development in freshwater (Hymanson presentation 1999, cited in Rudnick *et* *al.* 1999). Kamps (1937, cited in Peters 1938) found that spermatids required exposure to salinities of 8 ppt or more to develop properly, but Peters (1938) questioned this finding. Exposure to salt water may accelerate maturation (Peters 1938; Hymanson *et al.* 1999).

Mating. Mating has been observed in the field in salinities from around 5-6 ppt to 27 ppt and in the laboratory at up to 31 ppt, but preferentially occurs at 10-17 ppt (Peters1933, 1938; Hoestland 1948; Hymanson *et al.* 1999; Zhao presentation 1999). Mating that took place in freshwater in the laboratory did not result in spawning (Peters 1933).

Egg adherence. Spawning—the extrusion of the eggs and their attachment to hairs on the pleopods—occurs soon after mating. Several papers, generally citing earlier authorities, have reported that the event or stage with the highest minimum salinity requirement is the adherence of the eggs to the pleopods, requiring 25 or 26 ppt (Panning 1939; Hoestland 1948; Haahtela 1963; Ingle 1986; Cohen & Carlton 1997; Veldhuizen & Stanish 1999). Among the earliest authorities cited, Panning (1939) reported that mitten crab eggs would not properly adhere to the pleopods in low salinity water, stating that "the cementlike substance [that attaches the eggs to the hairs on the pleopods] hardens only in water that has a salt content of more than 2.5 percent [=25 ppt], according to F. Buhk." Panning did not provide a specific journal citation for his reference to Buhk, however Buhk (1938) reported that "experiments in previous years showed that attachment of the eggs after mating would work best in salt concentrations over 25 to 30 ppt,"[6] a statement indicating that over 25 ppt is an optimum rather than a minimum concentration. On the other hand, Peters (1938) reported that in experiments conducted at 10-16°C, eggs did not adhere at all below 17 ppt, and did not adhere properly at salinities of 23 ppt or less, falling off the pleopods within days.[7] At salinities of 26-32 ppt, most eggs remained adhered to the pleopods. These findings suggest an absolute requirement of over 23 ppt.

These laboratory data from the 1930s do not agree with more recent observations. Anger (pers. comm. 1999) reported that eggs adhere at 20 ppt or less. Chinese researchers, apparently based on field observations, report that mitten crab eggs attach successfully down to at least 15 ppt (Zhao pers. comm. 1999). In California, ovigerous females have been collected at salinities down to 6 or 10 ppt (Veldhuizen & Stanish 1999, Veldhuizen pers. comm. 1999), although it is not known at what salinities the eggs were extruded.[8]

Embryonic development and hatching. Zhao (pers. comm. 1999) states that embryos develop best at 15-17 ppt, or possibly up to 20 ppt, but that some successful development can occur between 3 and 27 ppt. Buhk (1938) reported that optimal hatching occurs at 23 ppt. Peters (1938) found that constant salinities below about 18 ppt led to fungal infections of eggs, though temporary exposures to 10 ppt (e.g. at low tides) did not damage eggs or precipitate infections.

Larval development. In laboratory studies in Europe, the highest survival rates were produced at salinities of 15 or 20 to 25 ppt for early stage larvae and 25 to 32 ppt for later stage larvae (Anger 1991). If reared at constant salinities through the larval period, survival was generally highest at 25-32 ppt. In these experiments, the permissible and optimal salinity ranges varied with

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6 "Die Versuche in den Vorjahren hatten ergeben, dass das Ankleben der Eier nach der Paarung am besten in Salzgehalten über 25 bis 30 ‰."

7 "Auffallenderweise verlief jedoch die Eiablage in Wasser von 5 ‰, 8 ‰, 11 ‰ und 14 ‰ anormal; es wurden nämlich in keinem Falle die Eier angeklebt. Diese quollen vielmehr unter dem Schwanzdeckel hervor und wurden in Aquarium verstreut. Erst in wasset von 17 ‰ und mehr Salzgehalt wurden die Eier in natürlicher Weise an die Haare der inneren Äste der Pleopoden angeklebt. Aber auch bei 17 ‰, 20 ‰ und 23 ‰ Salzgehalt hafteten die Eier nicht sehr fest, und in den meisten Fällen gingen sie den Weibchen in den nächsten Tagen wieder verloren."

8 Hieb's (2001) observation that in San Francisco Bay ovigerous females are found at higher salinities (mean=16.9 ppt) than non-ovigerous females (mean=10.9 ppt) or males (mean=10.2 ppt) is consistent with higher salinities being necessary or optimal for egg adherence or embryonic development.

temperature, being a few degrees broader at 18°C than at 12°C (Anger 1991). Chinese workers report optimal salinities for larval development at 13-26 ppt (Jiang pers. comm. 1998), or "around 15 ppt" (Zhao pers. comm. 1999). These statements from China suggest optimal salinities for larvae that are somewhat lower than those indicated by the European experiments.

Metamorphosis. The metamorphosis from megalopa to juvenile can apparently occur in salinities from freshwater to 32 ppt, with optimal salinities of 15-25 ppt at 15°C (Anger 1990, 1991). Megalopae reared through the zoeal stages at 32 ppt and then transferred to salinities of ≤20 ppt were more successful (greater survival and more rapid development to metamorphosis) than megalopae that had been reared at constant salinities of ≤20 ppt (Anger 1991). Chinese workers have found that late stage megalopae can be transferred directly from 15 ppt to 0 ppt without harm (Zhao presentation 1999).

Anger (1991) suggested a model of "ontogenetic migrations" during the mitten crab's larval development which fit the salinity preferences that he inferred from laboratory experiments. In this model, hatching occurs in estuaries at salinities around 20 ppt (with a range of 10-25 ppt). Early zoeal stages remain near the surface, and are transported seaward in net down-estuary surface currents, to higher salinity waters where the later zoeal stages develop. The megalopae move toward the bottom, where they are transported landward in net up-estuary bottom currents, back into fresher waters. Large estuaries with large freshwater inflows and well-developed "estuarine circulation" would thus provide appropriate conditions for retaining great numbers of larvae, moving them through these salinity ranges during development, and returning them to the river's mouth.

In addition to the above data on the salinity requirements of particular life stages, the failure of mitten crabs to become established in various low salinity areas where they have been released also suggests that they require certain minimum salinities for some part of their life cycle. In the North American Great Lakes, which are completely fresh with distant and difficult access to salt water, 12-14 adult crabs were collected between 1965 and 1997 (Nepszy & Leach 1973; Hemdal pers. comm. 1997; Niimi pers. comm. 2001). No eggs, larvae or juveniles have been reported from the Great Lakes, and mitten crabs are not believed to have ever been established in the Great Lakes region. Rather, the crabs collected in the Great Lakes are thought to be individuals transported from northern Europe in ballast water.[9]

In the Baltic Sea, surface salinities range from around 2 ppt in the north and east to less than 10 ppt in the western Baltic, with bottom salinities in the deeper basins ranging from 12 to 16 ppt (Sverdrup *et al.* 1942; Ekman 1953). Hundreds of adult mitten crabs have been collected in the Baltic but the data suggest to us that they have not become established there, although several authors have mapped and reported on them as if they were established (e.g. Panning 1939; Hoestland 1948, 1959; Grabda 1973; Christiansen 1969, 1977; Anger 1990; Clark *et al.* 1998).[10]

9 Almost all of these crabs were collected in western Lake Erie, with the furthest upstream individual collected at Detroit. In this system, brackish water is first encountered in the St. Lawrence River around Quebec. A mitten crab spawned there would have to migrate 400 km up the river to Lake Ontario, 200 km across the lake, 30 km through the Welland Canal, and 150-250 km across Lake Erie to reach the area where most of the crabs were collected.

10 European researchers gave differing responses to our inquiries about mitten crabs in the Baltic Sea. Janssen (pers. comm. 1995) reported the mitten crab is "not common in Baltic Sea area, as salinity seems to be too low for its reproductive process." Gollasch (pers. comm. 1999, 2000) stated that although some mitten crabs are found in the eastern Baltic each year, they cannot reproduce there and the nearest marine water, in the North Sea, is too distant for them to migrate. He confirmed that they cannot breed in the Baltic Sea because of low salinities, and that the crabs collected in the Baltic are adults that either arrived on ships, were carried on currents, or migrated through the Kiel Canal from the Elbe estuary. On the other hand, Anger (pers. comm. 2000) reported that the mitten has been "established" for several decades "practically throughout the entire Baltic

In Finland, for example, with near-shore surface salinities of 2-6 ppt, 66 adult mitten crabs were collected between 1933 and 1962, but no eggs, larvae or juveniles (Haahtela 1963). Mitten crabs have been reported in the Oder River (on the German-Polish border) and the Wista River (in eastern Poland), which flow into the Baltic, but these crabs may have migrated into these rivers as juveniles or adults via canals from the Elbe River on Germany's North Sea coast. Panning (1939), for example, states that in the 1920s mitten crabs from the Elbe River "found their way...eastward into the Oder through the waterways leading from the Elbe through Brandenburg," and that later "upon reaching maturity, they naturally moved on downstream into the Baltic in their hunt for salt water." The Oder, in turn, connects to the Wista through the Notec and Netze rivers and a canal near Bydgoszcz, and mitten crabs have been collected in this connecting link (Grabda 1973). Jazdzewski & Konopacka (1993) noted that the invasion of the Oder had "ceased nearly totally" by the 1940s, with only sporadic individual specimens collected in Poland's coastal or inland waters—thus significant numbers of crabs were found in the Oder River only during the period when crab populations in the Elbe watershed were exploding.

Even in Denmark, in the westernmost and saltiest part of the Baltic Sea, only 78 mitten crabs, all adults, were collected from 1927-1985 on both the Baltic and North Sea coasts (Rasmussen 1987), where surface salinities generally range from 10 to 25 ppt (Sverdrup *et al.* 1942). Out of 33 females recorded, only three carried eggs and "none of the eggs were healthy or able to develop" (Rasmussen 1987). Similarly, the eggs of 27 ovigerous females collected in May 1936 from the Kiel Canal (which connects the western Baltic to the Elbe estuary in the North Sea across the Danish peninsula; also called the Kaiser-Wilhelm or Nord-Ostsee canal) were in very poor condition and many were infected by fungus (Peters 1938). Salinities in the canal were 3-13 ppt. Although Panning (1939) reported that mitten crabs had "established a particular breeding ground in the region of the Danish Great and Lesser Belt in the Baltic," the very few records from this region suggest that breeding does not occur there. Throughout the Baltic, the small number of crabs collected and the fact that only adults have been found in these fresh or low salinity waters suggest that either reproduction or larval development are not possible at these salinities. The few crabs that have been collected could either have arrived by active migration though canals from the Elbe (through the Kiel Canal or the Elbe-Lübeck canals which connect directly to the Baltic, or through at least two canal system connecting the Havel River to the Oder River), or been accidentally transported by ships or barges.

Summary: Data from a variety of sources indicate that while metamorphosis and settlement from the megalops stage, juvenile and adult growth, and gonadal development can occur in fully fresh water, some minimum levels of salinity are required for reproduction and embryonic and larval development. Mating appears to require salinities of at least around 5-10 ppt, with optimal levels around 15 ppt; egg adherence appears to require salinities of at least around 15 ppt and possibly higher, with optimal levels possibly around 25-30 ppt; embryonic development and hatching require salinities of at least around 5-10 ppt, with optimal levels of around 15-25 ppt; and zoeal development requires salinities of at least around 10-15 ppt, with optimal levels of over 15 or 20 ppt. There are indications that some of the stages between mating and megalopa have upper salinity limits in the range of 25-35 ppt, but this is less clear. Large estuaries with well-developed estuarine circulation may expose larvae to optimal salinities for development.

Temperature

The temperature requirements reported for mitten crabs vary with their life stage, as discussed here and summarized in Table 5. As with salinity, the available information includes both experimental data and assessments of temperature requirements based on field observations.

Sea and in adjacent river systems," though possibly not breeding in the eastern parts because of low salinity. We concluded from the available data, discussed in the paragraph above, that mitten crabs are not established in the Baltic, except possibly near its mouth.

Table 5. Temperature ranges reported for mitten crabs

Life Stage	Possible Range	Optimal Range	References
Reproduction	≤18-20°C	–	Guo pers. comm. 1996
Mating	–	14-15°C	Zhao presentation 1999
Egg extrusion	–	9-12°C	Jin pers. comm. 1998
Embryonic development	–	15-20°C	Jin pers. comm. 1998
Hatching	–	15-20°C	Zhao presentation 1999
Larval development	12-18°C or higher	15-18°C or higher	Anger 1991
	–	20-25°C	Jin pers. comm. 1998
	–	≈25°C	Zhao presentation 1999
Juvenile and adult growth	4-32°C	–	Guo pers. comm. 1996
	–	15-25°C	Jiang pers. comm. 1998
	7-31°C	24-28°C	Zhao presentation 1999
	7-30°C	20-30°C	Hymanson *et al.* 1999

Hatching occurs in the estuaries from late winter to early summer, and larvae develop in the estuaries from spring through fall (Table 1). Guo (pers. comm. 1996) reported that mitten crabs cannot reproduce above about 18-20°C. Zhao (presentation 1999) reported that temperatures of 15-20°C are optimal for hatching, with eggs failing to emerge when temperatures are too low, and aborting when temperatures are too high. Anger (1991), in laboratory tests of larval development under varying salinity and temperature regimes, found that constant temperatures of 6 or 9°C were fatal to larvae, and that survival rates increased with increasing temperature from 12 to 18°C. Kim & Hwang (1995) obtained good survival from hatching through metamorphosis to juveniles at 25°C.

In Asia, the southernmost large population of mitten crabs is in the Oujiang River, where summer sea surface temperatures are around 26-27°C (Sverdrup *et al.* 1942; NOAA 1999; Table 6). The southern limit of their natural distribution is in Fujian province, where summer sea surface temperatures are around 26-28°C (Sverdrup *et al.* 1942; NOAA 1999); and they apparently became at least temporarily established in the Zhujiang River and other waters near Hong Kong, where summer sea surface temperatures are around 27-28°C (Sverdrup *et al.* 1942), and the highest mean monthly temperature in adjacent Dapeng Bay is 30°C in August (Yu *et al.* 1988).[11] The southernmost established population in Europe is in the Tagus River system, where summer sea surface temperatures are around 18-19 °C (Sverdrup *et al.* 1942; NOAA 1999) and summer estuary temperatures are around 24-25°C (Moreira *et al.* 1992; Cabral & Costa 1999). Mitten crabs arrived at but did not become established in the Languedoc lagoons on the French Mediterranean coast, where water temperatures in August were 20.5-22.5°C (Petit 1960; Petit & Mizoule 1974; Noel pers. comm. 1999). Juvenile crabs were observed in south San Francisco Bay tidal sloughs and the lower reaches of freshwater creeks with summer temperatures of 20-31°C (Halat 1996; Rudnick *et al.* 1999). Juvenile and adult crabs rear in upper estuaries or rivers, predominantly in shallow areas with low water velocities, and various workers have reported that temperatures of 15-30°C are needed in these areas for good growth (Jiang pers. comm. 1998; Hymanson *et al.* 1999; Zhao presentation 1999). Zhao (pers. comm. 1999) reports that in culturing crabs "it is preferable not to exceed" 31°C at any life stage, and Guo (pers. comm. 1996) reported that the highest temperature they can withstand is about 32°C.

11 The southernmost crab in the genus, *Eriocheir hepuensis*, inhabits the Nanliu River in Guangxi province on the northern Gulf of Tonkin, where summer sea surface temperatures are above 29°C (Sverdrup *et al.* 1942).

Table 6. Summary of latitude and temperature data for watersheds that have supported large mitten crab populations

	Latitude	Sea Surface Temperature		Estuary Temperature	
		Winter	Summer	Winter	Summer
	(°N)	(°C)	(°C)	(°C)	(°C)
Liao	41	≤0	23-24	–	–
Hai	39	0	24	–	–
Yangtze	31.5	8-10	26-27	–	–
Oujiang	28	10-13	26-27	–	–
Elbe/Havel	54	3	17-18	4-6	19
Weser	53.5	3	17-18	–	–
Eems/Dollard	53.5	3-4	17	–	19-21
Rhine	52	4-5	17-18	–	–
Scheldt	51.5	5	17-18	<10	20-23
Thames	51.5	5-7	16-17	5-10	17-23
Gironde/Garonne/Dordogne	45.5	10	19	8	20-24
Tagus	39	14	19	14-15	23-25
Sacramento/San Joaquin	37.5	11-12	14-15	7-12	16-22

Data are summarized from Table 2. Sea surface temperatures are from Sverdrup *et al.* (1942).

Mitten crabs may be present in estuaries in the winter as mating adults, as eggs, or as juveniles or adults rearing in the upper parts of the estuary (Table 1). Mitten crabs have occurred in great abundance in estuaries in the North Sea region where winter sea surface temperatures are typically 3-6°C (Sverdrup *et al.* 1942; NOAA 1999), and in moderate or great abundance in the Hai and Liao rivers in China, where winter sea surface temperatures are 0°C or less (Sverdrup *et al.* 1942). Behavioral adaptations may help these crabs to cope with the cold. Elton (1936) reported that in Europe in the winter, small and medium-sized mitten crabs move into deeper water to escape the cold, and Peters (1933) reported that in the Elbe estuary in winter most mitten crabs are found in the "warm" 4°C, deep water. Adults can also survive mild frosts by burying in the mud (Anger pers. comm. 1999), and survive in burrows at temperatures of 0°C (Dai pers. comm. 1996, cited in Vincent 1996). Guo (pers. comm. 1996, cited in Vincent 1996) reports that adults can tolerate temperatures of 0°C for up to seven days, though Peters (1933) found that crabs that were frozen in experiments or in the environment did not survive. In China, adult crabs "almost stop feeding" at 7°C, but can live through the winter under ice at 4°C (Zhao presentation 1999). Guo (pers. comm. 1996) reported that they can tolerate temperatures down to 4°C. Vincent (1996) argued that the cold winter of 1962-63 eliminated mitten crabs from the Seine watershed.

Summary: Mitten crabs have become abundant in river systems with typical winter temperatures in the estuary as low as 5-10°C and surface temperatures in the adjacent seas below 0°C; and summer temperatures in the estuary as high as 23-25°C and in the adjacent seas as high as 26-27°C (note that estuary temperature data is not available for all systems, and the true range may be broader). Estuary temperatures of around 15-25°C in the spring and summer are reported to be necessary for good hatching success and larval development, with larvae dying in laboratory experiments in temperatures below 12°C. Growing season (primarily summer) temperatures of 15-30°C are needed for good growth in the juvenile and adult rearing areas in the upper estuary and river, though they can survive temperatures from around 4° to 31-32°C.

Pollution
Chronic discharge of untreated industrial effluent is thought to have reduced wild crab populations in China since the 1960s (Jiang pers. comm. 1998; Hymanson *et al.* 1999). Pollution may have been a factor in reducing mitten crab populations in northern Europe after the population boom of the 1930s (Anger 1990; Türkay pers. comm. 1995; Mares pers. comm. 1998), and in the Tancarville Canal area of the Seine estuary after the 1950s (Vincent 1996). Gollasch (1999) suggested that pollution may reduce mitten crab densities by reducing the abundance of prey, thereby increasing the rate of cannibalism in mitten crabs. Recent increases in mitten crab populations in Germany have also coincided with improvements in water quality related to the construction of sewage plants and the closing of former East German factories (Fladung pers. comm. 1999; Gollasch 1999). On the other hand, Peters (1933) reported that mitten crabs lived in the polluted waters of Hamburg Harbor and in extremely oil-contaminated waters; and Ingle (1986) suggested that the mitten crab's "population explosions seem to have coincided with a reduction or disappearance of fishes, natural predators of mitten crabs," caused by declines in water quality.

Summary: It has been suggested both that pollution reduces mitten crab populations and, contrarily, that pollution enhances mitten crab populations by reducing their predators; but there has been no significant study of the mechanisms or net effect of pollution on mitten crab population dynamics.

Primary Productivity
Gross *et al.* (1988) argued that anadromy and catadromy evolved in fishes in response to the differing availability of food resources—roughly correlated with primary productivity—in the ocean and fresh water. They assembled evidence showing that in the tropics (below about 35° latitude), primary productivity in fresh water vastly exceeds that in the ocean, and catadromy is more common than anadromy. They argue that in the tropics it is advantageous for fish to migrate into the productive freshwater systems to grow to maturity, explaining the greater frequency of catadromy than anadromy. They showed that in temperate latitudes (about 35-70° latitude), ocean primary productivity is generally higher and freshwater primary productivity generally lower than at lower latitudes,[12] and anadromy is more common than catadromy.

If similar arguments apply to crabs, mitten crabs' distribution could be limited at higher latitudes by declining freshwater productivity. While there are no direct data on this, it is consistent with the greater species diversity and abundance of river crabs, both resident and migratory, in tropical and subtropical waters (Ng 1988); and with observations that large mitten crab populations only develop where freshwaters have extensive submersed vegetation.

Summary: A study of catadromy in fishes suggests that this migratory pattern should be less successful as freshwater primary productivity declines, which tends to occur at increasing latitudes. This effect could limit mitten crabs' poleward distribution.

Water Velocity in the River
Hymanson *et al.* (1999) and Haahtela (1963, citing Panning 1952) state that fast-flowing rivers are unsuitable for mitten crabs. Attrill & Thomas (1996) suggest that a breeding population was able to establish in the Thames River in 1988-92 only because of low river discharge and low water velocities during a drought. However, while access to large areas of slow, shallow water in the upper estuary or river is apparently necessary for the development of large populations (Zhao presentation 1999), we found little evidence that higher water velocities prevent the establishment or impede the migration of mitten crabs. During experimental tests of a travelling screen conducted in a flume with a concrete bed, mitten crabs were observed to move easily against currents up to about 0.55-0.60 m/s, but had a difficult time maneuvering or were swept downstream at higher

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12 They are roughly the same, however, in absolute terms; that is, in temperate latitudes primary productivity per square meter is similar in the oceans and in fresh water.

velocities. In a flume with a very smooth bed, mitten crabs were unable to progess upstream even against currents of 0.3 m/s, the lowest velocity tested, except sometimes by hugging the wall. The crabs in these experiments, however, were in poor condition, and were generally less active than crabs observed in the field, perhaps in part because of the cold water temperatures used in the experiments (Hanna pers. comm. 2001; Hess pers. comm. 2001). The condition of these experimental crabs, uncertainty about how the roughness of the flumes compares to field conditions, and the possibility that crabs may adjust their behavior in rivers with strong currents (such as travelling in the shallow margins where currents are slower, or travelling on shore beside a river in reaches with fast currents), make it difficult to draw conclusions from these experimental observations about how current velocities affect crab migration in the field. From field observations, it has been reported that current velocities up to 1.5 m/s do not limit upstream migration in Germany (Fladung pers. comm. 1999).

Summary: There are no good data on what current velocities will block the upstream movement of mitten crabs, although it has been reported that they can migrate against currents of at least 1.5 m/s.

<u>Barriers in the River</u>

Juvenile and adult mitten crabs are able to climb over some barriers, and can leave the water and walk around barriers that are too high or provide inadequate footing for climbing (Peters 1933; Panning 1939). Mitten crabs are known to be one of the best climbers among crabs (McLaughlin 1982). Juvenile crabs can climb short distances up vertical concrete walls (Zhao presentation 1999; Hymanson *et al.* 1999), and have escaped from 6 m deep concrete holding tanks that were quarter-filled or half-filled with water (Hess pers. comm. 2001). Adults can live out of water in a dry environment for about a week (Peters 1933; Elton 1936; Veldhuizen & Stanish 1999), and have survived up to 38 days in a damp meadow (Peters 1933).

Mares (pers. comm. 1998) reported that migrating crabs encountering lock systems "simply wait until the lock-gates open, and if they remain closed they continue their voyage over land. During September 1982 this happened in the city [of] Heemstede (Netherlands): they left the water and continued their voyage through the city in such large numbers that the people called upon the government to protect them; the crabs climbed walls, walked over the roofs, were found in the houses...No one was hurt but there was quite a panic." Panning (1939), in a vivid passage, similarly reported that "when crabs are jammed below a dam they try in many ways to get by the obstacle. They crawl up on the walls and finally out on the shore, so as to pass the dam by land...During warm summer nights the shore region is black with crabs; one cannot take a step without treading on them. In places when a dam is close to a city, it happens occasionally that mitten crabs land on city streets and finally even penetrate into houses. This happened in 1931 in Rathenow on the Havel, in 1936 in a suburb of Magdeburg, and in 1938 in Calbe on the Saole." Although large congregations on land have not been reported in California, there are several reports of mitten crabs wandering on land at night or being found in swimming pools (Hieb pers. comm. 1997; Lie pers. comm. 1998).

In the Sacramento River in 1998, some upstream migrating crabs climbed over weirs in the Sutter and Yolo bypasses, including the 2.7 m high Sacramento Weir, and other crabs left the water and walked around it (Hieb & Veldhuizen 1998; Veldhuizen & Stanish 1999; Hymanson pers. comm. 1999); and have been found above small (<2 m high) dams in tributaries to south San Francisco Bay (Rudnick pers. comm. 2001). In the Thames River in England (Attrill pers. comm. 1999) and the Elbe River in Germany (Panning 1939; Fladung pers. comm. 1999), migrating mitten crabs have climbed over or walked around numerous weirs and locks, in some cases possibly passing through locks or up or down fish ladders. They have apparently passed through locks in both the Kiel Canal (passing from the North Sea into the Baltic; Peters 1938; Panning 1939; Gollasch pers. comm. 2000) and the Midi Canal (traveling from the Atlantic into the Mediterranean; Petit 1960), and presumably in other European waterways as well. However, in the Yangtze River in China, 6 m-high locks prevent crabs from moving into their historical habitat in adjoining lakes. These locks have both vertical sections and sections angled 45° back from the water. While an occasional crab may surmount the locks, most are stopped (Zhao presentation 1999; Hymanson *et al.* 1999).

In small tributaries to south San Francisco Bay, crabs had not spread upstream past concrete-lined channels in 1995-96, but they were found in and above such channels by 1999 (Halat 1996; Rudnick *et al.* 1999, 2000)

Summary: Mitten crabs are capable of climbing over concrete structures at least 3-4 m high, although it is reported that in China 6 m high vertical and sloped barriers stop most crabs. Mitten crabs can also pass through lock systems and possibly climb fish ladders, or leave the water and walk around barriers where the terrain is suitable.

<u>Upstream Distance</u>

Although a few mitten crabs have been reported as far upstream as 700 km up the Elbe River at Prague and 1,400 km up the Yangtze River, the furthest upstream reports of high densities of mitten crabs are only 450 km from the mouth (about 350 km from the head of the estuary) in the Elbe River (Panning 1939).

Summary: In appropriate cricumstances, high densities of mitten crabs can spread up a river to at least 350 km above the head and 450 km above the mouth of the estuary, although smaller numbers of crab may proceed much higher.

<u>Isolation from the Sea</u>

Although mitten crabs apparently require salinities of at least 15 ppt for some phases of reproduction and development (see above), the question arises as to whether they could become established in inland saline lakes with freshwater tributaries. Wolff & Sandee (1971) reported that mitten crabs were common to abundant along the Netherlands coast and in rivers and tidal areas, but were absent from "brackish, non-tidal inland waters" in the Netherlands. In China, there are no natural landlocked populations of mitten crabs. Mitten crabs are successfully bred and reared to megalops stage in inland situations in artificial seawater (sea salt with water added) of the proper salinities, and there are plans to try and rear crabs in some interior lakes in the Xinjiang and Inner Mongolia Autonomous Regions. These lakes are partly alkaline and partly fresh, and it appears that the intent is to breed and rear to megalops stage in artificial seawater, and then rear to adults in the freshwater portions of these lakes (Zhao pers. comm. 1999). Dr. Zhao was dubious about the potential for crabs to become established and reproduce in interior, alkaline lakes due to concentrations of potassium, magnesium and calcium ions that differ from seawater, but was not aware of any data on the crab's tolerance to variations in these concentrations (Zhao pers. comm. 1999). Barrington (1979) reported on *Eriocheir*'s strong osmoregulatory ability, remaining hyper-osmotic in freshwater and hypo-osmotic in hypersaline conditions.

Summary: There are no self-sustaining, land-locked populations of mitten crabs. Though mitten crabs can reproduce and develop in artificial seawater, and as adults can tolerate salinities from freshwater to hypersaline, nothing is known about their ability to function in water with ionic proportions that differ from seawater, as is typical of inland saline lakes.

Potential Distribution of Mitten Crabs Relative to U.S. Bureau of Reclamation Facilities

<u>Columbia River System</u>

Estuary characteristics. The Columbia River rises on the western slope of the Rocky Mountains in Canada, runs southward into Washington and then turns westward, forming the border between western Washington and Oregon, before entering the ocean at about 46.5°N latitude. The estuary has two main channels connected to a network of smaller channels interspersed with extensive sandbanks, tidal flats and marshes. The estuary as defined by the Columbia River Estuary Data Development Program (CREDDP) extends to 75 km from the mouth, and covers some 412 km^2, of which 59 km^2 are marsh and 39 km^2 are tidal flats (Simenstad *et al.* 1990). Salinity intrusion typically extends around 50 km and is largely confined to the estuary's two main channels (Hamilton 1990). The area within reach of the tides extends 235 km to Bonneville Dam and includes about 625 km^2 with a mean depth of abouT 5 m at mid-tide (Simensted *et al.* 1990; Hamilton 1990; NOAA 1998; USACE 1999).

Within the estuary, large peripheral bays with low water velocities support highly productive benthic habitat (Simenstad *et al.* 1990). The estuary has a 660,500 km^2 watershed that extends into seven states and Canada (Simenstad *et al.* 1990; Prahl *et al.* 1998; USACE 1999). Mean annual discharge is about 7,300-7,800 m^3/s, ranging from extreme low flows of around 2,000-3,000 m^3/s to extreme high flows around 15,000 m^3/s (Hamilton 1990; Prahl *et al.* 1998; NOAA 1998; USACE 1999; though Simenstad *et al.* 1990 report mean annual discharge of about 5,100 m^3/s). In June 1948, peak daily mean flow reached 26,000 m^3/s (Fuhrer *et al.* 1996). Discharge is highest in late spring (corresponding to peak snowmelt in the Cascade Mountains) and lowest in late summer to early fall (Fuhrer *et al.* 1996; Prahl *et al.* 1998). Vertical stratification in the estuary varies from fully mixed to salt wedge conditions (Hamilton 1990).

Sea surface temperatures off the mouth of the estuary are typically around 9-10°C in the winter and 14-15°C in the summer (Sverdrup *et al.* 1942; NOAA 1999), while estuary temperatures range from around 3-6°C in winter to 20-22°C in summer (University of Washington 2001). Some temperature data for the Columbia River system are provided in Table 7.

Table 7. Some water temperature data for the Columbia River system

Location	Period	Mean	Range of Measures	References
Sea surface off the mouth of the Columbia River	Jan 1999	9.2°C	–	NOAA 1999
	Feb	9-10°C	–	Sverdrup *et al.* 1942
	Jul 1999	14.4°C	–	NOAA 1999
	Aug	14-15°C	–	Sverdrup *et al.* 1942
Columbia River estuary at 21 km from mouth at 9 m depth	Apr 1980	–	9°C	Bottom & Jones 1990
	Jun-Aug 1980	–	13-16°C	
	Oct 1980	–	13°C	
Columbia River at 45 sites ≈25-350 km from mouth	Jun 1992	–	17-18°C	Prahl *et al.* 1998
Columbia River at Longview, at head of estuary about 100 km from mouth	Jan 1967-68	–	3-6°C	University of Washington 2001
	Feb 1967-68	–	4-6°C	
	Mar 1967-68	–	7-9°C	
	Aug 1967-68	–	20-22°C	
Columbia River at Bonneville Dam Forebay, 235 km from mouth	Jan 1990	–	6.7-7.0°C	University of Washington 2001
	Feb 1990	–	5.0-5.6°C	
	Mar 1990	–	5.0-7.8°C	
	Aug 1990	–	21.1-21.7°C	
Columbia River at Warrendale	1974-83/93	–	2-22°C	USDOE 1995
	1981-84	12°C	–	
	1990-95	13°C	–	

Columbia River at Umatilla	1954-57 1974-83/93 1975-78 1990-95	11°C – 12°C 11°C	– 1-21°C – –	USDOE 1995
Columbia River at Richland, 539 km from mouth	1954-57 1974-83/93 1990-95	11°C – 12°C	– 1-21°C –	USDOE 1995
Columbia River at Priest Rapids Dam, 639 km from mouth	1954-57 1974-83/93 1990-95	10°C – 13°C	– 1-24°C –	USDOE 1995
Columbia River at Rock Island Dam, 730 km from mouth	1954-57 1974-83/93 1990-95	10°C – 11°C	– 1-24°C –	USDOE 1995
Columbia River at Lake Entiat, 763 km from mouth	annual minimum annual maximum	– –	3°C 18°C	Chelan County PUD 2001
Columbia River at Grand Coulee Dam, 960 km from mouth	1974-83/93 1990-95	– 9°C	1-19°C –	USDOE 1995
Willamette River at Portland	Feb 1990 Mar 1990 Aug 1990	– 8.4°C –	2-8°C – 21-24°C	University of Washington 2001
Willamette River at 4 sites in lower 27 km	Jun 1992	–	19.5-20.5	Prahl *et al.* 1998
Tualatin River at 16 km from mouth	Jul 1994, 1995 Nov 1994, 1995	– –	18.7-24.4°C 5.4-12.0°C	Risley & Doyle 1997
Tualatin River at 62 km from mouth	Jul 1994, 1995 Nov 1994, 1995	– –	12.7-21.8°C 5.1-11.5°C	Risley & Doyle 1997
Tualatin River at 95 km from mouth	Jul 1994, 1995 Oct 1994, 1995	– –	8.2-12.7°C 8.4-17.4°C	Risley & Doyle 1997
Scoggins Creek at Henry Hagg Dam	May 1994, 1995 Oct 1994, 1995	– –	6.8-8.8°C 13.0-18.4°C	Risley & Doyle 1997
Yakima River, below Prosser Dam	Apr-Jul 1998 summer	– –	11-24°C to >25°C	McMichael *et al.* 1999

<u>Columbia River System: (a) Main Stem of the Columbia River</u>

River characteristics. The Columbia River runs for 1,984 km from its headwaters in British Columbia through Washington and Oregon. Its largest tributary, the Snake River, enters at 523 km above the Columbia's mouth, and the entire watershed covers 660,500 km^2 (Prahl *et al.* 1998). There are over 250 dams and reservoirs and 150 hydroelectric projects in the watershed, including 18 main stem dams on the Columbia and the Snake rivers (USACE 2001a). Extensive hydroelectric development has turned the United States portion of the main stem Columbia River into a series of slow-moving reservoirs punctuated by 11 large dams (Sherwood *et al.* 1990; Prahl *et al.* 1998; USACE 1999) (Tables 8 and 9). In the 960 km below Grand Coulee Dam, the only remaining free-flowing segments are the lowest 235 km of the river below Bonneville Dam, and about 80 km below Priest Rapid Dam (Prahl *et al.* 1998). The reservoirs are characterized by a downstream flow of at least 0.15 m/s, oxygen saturation at all depths, low sulfide levels, and little temperature variation across depths. Temperatures generally range around 2-7°C in the winter and around 17-22°C in the summer (Table 7).

Table 8. Dams on the main stem of the Columbia River in the United States

Name	Operator	Distance to mouth (km)	Structural Height (m)	Hydraulic Height (m)	Navigation Lock Lift (m)
Bonneville Dam	USACE, Portland District	235	58	13	21
The Dalles Dam	USACE, Portland District	308	61	61	27
John Day Dam	USACE, Portland District	347	78	72	34
McNary Dam	USACE, Walla Walla District	470	55	37	25
Priest Rapids Dam	Grant County PUD	639	56	49	no lock
Wanapum Dam	Grant County PUD	669	54	48	no lock
Rock Island Dam	Chelan County PUD	730	39	22	no lock
Rocky Reach Dam	Chelan County PUD	762	52	37	no lock
Wells Dam	Douglas County PUD	829	56	54	no lock
Chief Joseph Dam	USACE, Seattle District	877	72	71	no lock
Grand Coulee Dam	USBR	960	168	116	no lock

Sources: USBR 2001; USACE 2001a,c; Athearn pers. comm. 2001

Structural height is the vertical distance between the lowest point of the excavated foundation and the top of dam, and is often what is given as the 'height' of a dam. Hydraulic height is the vertical distance from the original streambed or the lowest outlet works, whichever is lower, and the elevation of the maximum controllable water surface behind the dam. In many cases hydraulic height is a reasonable estimate of the minimum height that would have to be scaled by an upstream migrating crab in order to pass over a dam, although it may be an overestimate if the maximum water surface is controlled by gates above the spillway crest or if the lowest outlet works are substantially below the elevation of the streambed at the dam axis.

Table 9. Reservoirs on the main stem of the Columbia River below Grand Coulee Dam

Dam	Reservoir	Surface Area (km^2)	Capacity (10^6 m^3)	Length (km)
Bonneville Dam	Lake Bonneville	83	875	73
The Dalles Dam	Lake Celilo	45	410	39
John Day Dam	Lake Umatilla	210	2,922	123
McNary Dam	Lake Wallula	150	1,620	101
Priest Rapids Dam	Priest Rapids Lake	29	257	30
Wanapum Dam	Wanapum Lake	65	833	61
Rock Island Dam	Rock Island Reservoir	10	160	32
Rocky Reach Dam	Lake Entiat	42	561	57
Wells Dam	Lake Pateros	42	550	56
Chief Joseph Dam	Rufus Woods Lake	34	732	83

Sources: USBR 2001; USACE 2001a,c; Athearn pers. comm. 2001

USBR facilities. USBR's Columbia River Basin Project, built for power generation and irrigation, is a large system of dams, powerplants, pumping plants, irrigation canals and reservoirs. The first USBR facility on the main stem of the Columbia River is Grand Coulee Dam, 960 km from the mouth of the river. The Grand Coulee facility consists of Grand Coulee Dam, Franklin D. Roosevelt Lake, the Grand Coulee Powerplant Complex, a pump-generating plant and switchyards. The powerplants are located on either side of the downstream face of the dam. There are over 481 km of main canals, about 3,206 km of lateral canals, and 5,610 km of drains and castaways.

Barriers. There are ten large dams on the Columbia River downstream of Grand Coulee Dam. Five are operated by three districts of the U.S. Army Corps of Engineers, and five are operated by Public Utility Districts in three Washington state counties (Table 8 and Fig. 3). The four lowest dams have navigation locks that are opened about four to five times per day. There are no navigation locks on the Columbia River dams upsteam of the Snake River confluence (USACE 1999; Athearn pers. comm. 1999).

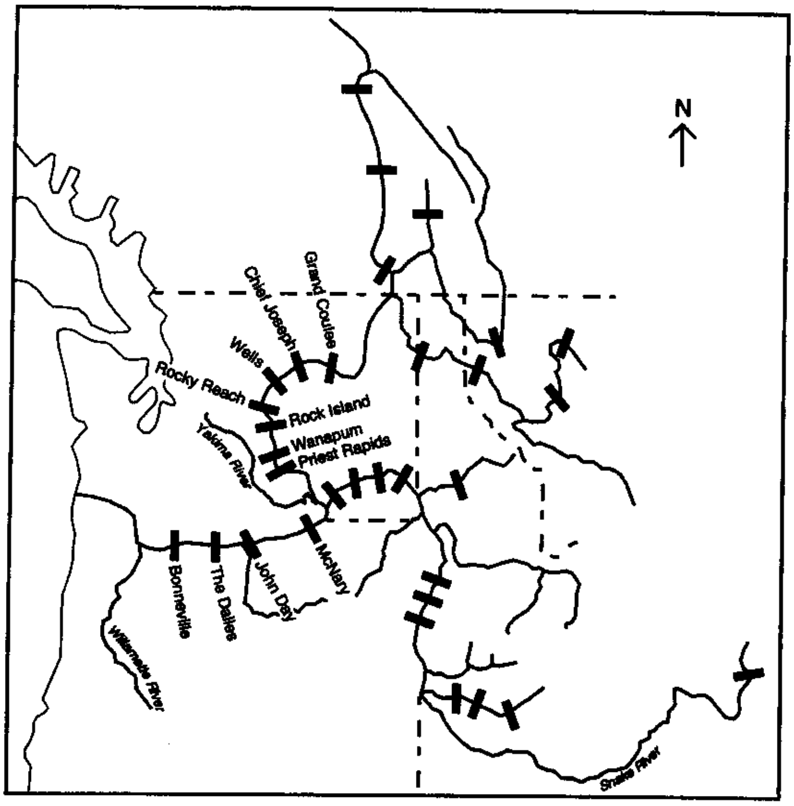

Figure 3. Columbia River System

The nine lowest dams have fish ladders to allow for the upstream migration of adult salmon and steelhead trout. These ladders operate continuously except for an annual maintenance period that normally takes up to two weeks and is scheduled for some time between December and February. The four lowest dams have multiple fish ladders, and maintenance is normally scheduled so that at least one ladder is functional at all times. The ladder systems consist of collection channels; some combination of weirs with overflow, submerged orifices or vertical slots; approach, holding and exit pools; counting sections; and auxiliary water supply systems. The fish ladders are often several hundred meters long, with slopes between 1:20 and 1:10. To increase the volume of water released from the ladders sufficiently to attract migrating fish, auxiliary supply systems deliver water into the lower portions of the ladders through diffuser gratings. These gratings prevent fish from entering the auxiliary systems and becoming stranded. Flows through these gratings are in the range of 0.3 m/s, and flows past the ladder weirs (either overflow or through the submerged openings) are 2-3 m/s (USACE 1981; Johnson pers. comm. 1999; Athearn pers. comm. 2001).

Juvenile fish go downstream either through the turbines, over the dam spillway, through the ice and trash sluiceway (at The Dalles Dam), or through juvenile fish bypass systems (at Bonneville, John Day and McNary dams, which use fish screens to guide fish away from the turbines and then either into channels that carry the fish to the river below the dam, or (at McNary Dam) into a holding area for collection and transport by barge or truck to a release site downstream of Bonneville Dam). Juvenile bypass lasts from late March into December, and transport from McNary Dam normally lasts from June until late November or early December (USACE 1981, 1999, 2001a,b,c; Johnson pers. comm. 1999; Athearn pers. comm. 2001).

Suitability for mitten crabs. Summer and winter sea surface temperatures off the mouth of the Columbia River, and summer estuary temperatures, are within the range reported for watersheds with large mitten crab populations (Table 10). Winter estuary temperatures (3-6°C) are slightly below this range, but as we lack estuary temperature data for the estuaries with the coldest winter sea surface temperatures (Liao and Hai river estuaries), the actual range may be broader. The size of the estuary, river and watershed, and the volume of discharge, are also within the range of watersheds with large mitten crab populations (Table 11). The estuary is highly productive with extensive, shallow salt, brackish and freshwater habitat, which is favorable for mitten crabs. The low gradient, tidally-influenced reach of the lower river below Bonneville Dam has summer temperatures within the range (15-30°C) that supports good juvenile and adult growth. The Columbia River estuary and lower river thus appear to be highly suitable habitat for mitten crabs, capable of supporting an abundant population.

However, to reach the USBR facilities at Grand Coulee Dam, mitten crabs spawned in the estuary would have to migrate up nearly 1,000 km of river (to about 725 km above the reach of the tides) and pass ten large dams and reservoirs. To accomplish this, the crabs would have to make their way either through navigation locks (on the four lowest dams), up fish ladders (on the nine lowest dams), or leave the water and walk around the dams; and would also have to navigate upstream through the reservoirs.

Table 10. Latitude and temperature ranges for watersheds with large mitten crab populations, and data for assessed watersheds

	Latitude	Sea Surface Temperature		Estuary Temperature	
		Winter	Summer	Winter	Summer
	(°N)	(°C)	(°C)	(°C)	(°C)
Range for watersheds with large mitten crab populations	28 to 54	≤0 to 10-13	14-15 to 26-27	4-6 to 14-15	16-22 to 23-25
Columbia	46.5	9-10	14-15	3-6	20-22
Rogue	42.5	10	14-15	7.5	20-21
Klamath	41.5	10-11	14-15	6-8	17-23
Texas Coastal Bend	26-29	20-22	28-29	8-16	23-32

Data are summarized from Tables 2 and 7. Sea surface temperatures are from Sverdrup *et al.* (1942). Note that estuary temperature data are not available for the Chinese estuaries, which include those with the coldest winter and warmest summer sea surface temperatures; thus the actual range for estuary temperatures is probably broader than shown here.

Table 11. Range of size and discharge data for watersheds with large mitten crab populations, and data for assessed watersheds

	Estuary Area (km²)	River Length (km)	Watershed Area (km²)	Discharge Annual Mean (m³/s)	Discharge Range (m³/s)
Range for watersheds with large mitten crab populations[a]	225 to 12,000	338 to 6,300	12,650 to 1,959,000	100 to 34,000	30 to 70,000
Columbia River estuary[b]	≈500	1,984	660,500	7,300-7,800	2,000-15,000
Rogue River estuary[b]	<2	346	13,000	300	35-460
Klamath River estuary[b]	<2	–	40,400	–	45-3,800
Lavaca/Navidad rivers estuary[b,c]	1,140	966	>109,000	150-177	–
Nueces/Frio rivers estuary[b,c]	538	507	>43,500	25-34	–

[a] Data summarized from Tables 2 and 3.

[b] Data summarized from text and accompanying tables.

[c] Data are given for Matagorda Bay system (Lavaca/Navidad rivers estuary) and Corpus Christi Bay system (Nueces/Frio rivers estuary). For Lavaca River alone the river length is 185 km, watershed area is 5,900 km^2, and mean discharge is 23 m^3/s; for Nueces River alone length is 507 km, watershed is 43,500 km^2 and discharge is 24 m^3/s (Table 26). For data on the entire Texas Coastal Bend Estuarine complex, see Table 25.

The navigation locks are single-lift locks with lift heights of 21 to 34 m. The vertical distance to be surmounted in each case would be around 6 m less (Athearn pers. comm. 2001). Mitten crabs are not good swimmers, but might be carried upward by turbulence as a lock is filled, or could perhaps climb the submerged concrete wall at the head of a lock when vessels are locked through upstream. Mitten crabs have escaped from 6 m deep, concrete-walled holding tanks that were only quarter- to half-filled with water (Hess pers. comm. 2001), and large numbers of mitten crabs have migrated through low head locks in Europe. Although the locks on the four lowest Columbia River dams have higher lifts, it may be possible for large numbers of upstream-migrating mitten crabs to make their way through the locks. The dams further upstream, however, do not have navigation locks.

To migrate up past any of the nine lowest dams via their fish ladders, a mitten crab would have to climb up a long series of pools extending over several hundred meters, either going through the submerged orifices in the weirs between the pools or climbing over the weirs against flows of 2-3 m/s, then pass from the holding pools past counting stations to the river forebay behind the dam. Although crabs could pass from the ladders through the diffuser gratings into the auxiliary water systems (see Foomote 13), these provide no feasible route to the upstream side (Athearn pers. comm. 2001).

While mitten crabs may be able to leave the water and walk around some obstructions—at Bonneville Dam, for example, crabs could walk over a 182 m strip of grass on an island between the dam structures (USACE 1999)—the surrounding steep terrain would make it difficult or impossible for crabs to walk around most of the dams (Athearn pers. comm. 1999).

The ten reservoirs below Grand Coulee Dam are large (up to 123 km long; Table 9), with good water quality, and small net downstream flow velocities (≤0.15 m/s; Johnson pers. comm. 1999). While these conditions do not suggest any outright barrier to mitten crab migration, the modest directional cues provided by small downstream current velocities in large reservoirs may further reduce the number of crabs successfully negotiating the migration route.

Overall, even if mitten crabs became very abundant in the Columbia River Estuary, it seems extremely unlikely that they would reach Grand Coulee Dam and the associated USBR facilities in any significant numbers, if they could reach it at all. While large numbers of mitten crabs have migrated as far as 450 km up rivers in Europe, the distance to Grand Coulee Dam is over twice that. The crabs would have to migrate past ten large dams, either passing through high-lift navigations locks (present on four of the dams), climbing long fish ladders (present on nine of the dams) or bypassing the dams on land, and navigate through ten large reservoirs.

Although mitten crabs are unlikely to directly affect the USBR facilities, large numbers of crabs in the lower river might affect the migration of salmonids to the USBR facilities. Migrating crabs packing into fish ladders or fish bypass channels during periods of salmon migration, or large numbers of crabs loaded with fish into transport trucks or barges, could impede the operation of these systems, increasing fish mortality and interfering with transport (Brown 1998; Siegfried 1999; Wynn *et al.* 1999a, 1999b; Veldhuizen & Stanish 1999; Bridges 2001).[13] A large crab population in the lower river and estuary might also reduce the food resources or vegetative cover available to downstream migrating smolts and juveniles. If the operation of USBR's Columbia River facilities could be affected through regulations or other legal instruments by changes in the river's anadromous salmonid populations, then a large mitten crab population in the lower reaches might have an indirect impact on the operation of USBR facilities.

Columbia River System: (b) Willamette River, Tualatin River and Scoggins Creek
River characteristics. The Willamette River enters the Columbia River 164 km above its mouth. It runs for nearly 480 km and drains a 29,500 km^2 watershed (Fuhrer *et al.* 1996; Prahl *et al.* 1998). The Tualatin River enters the Willamette River from the west 46 km above its mouth. The Tualatin is 128 km long and has a 1,850 km^2 watershed (Fig. 4). Scoggins Creek enters the Tualatin River 97 km from its mouth. USBR facilities are located on Scoggins Creek, with associated facilities on the Tualatin River (Risley & Doyle 1997; ODFW 1990; Tualatin River Watershed Council 1999; USGS 2000).

The lower Columbia River and the lower Willamette River are deep and slow, with meandering reaches, side lakes and marshes (Dean Smith and Associates 1995; Tualatin Valley Watershed Council 1999; Wade pers. comm. 1999). The average water velocity in the lower Willamette River up to the confluence with the Tualatin River is about 0.3 m/s. The tides affect the Willamette River up to Willamette Falls, about 43 km from its mouth (Tualatin Valley Watershed Council 1999; Wade pers. comm. 1999). Discharge is greatest from winter to early spring (Fuhrer *et al.* 1996).

Most of the Tualatin River below the mouth of Scoggins Creek is slow and meandering, part of which has been described as resembling a slow moving lake during summer low flow periods (Risley & Doyle 1997; Rounds *et al.* 1999). The river sections have been characterized as follows: a 39 km-long headwaters reach, from the headwaters to 8 km below the mouth of Scoggins Creek, with an average slope of 14 m/km; below that a 35 km-long meandering reach, with an average slope of 0.2 m/km; below that a 49 km-long backwater reach extending to a low head dam (Lake Oswego Diversion Dam), 5 km above the river mouth, with an average slope estimated at 0.015 m/km; and below that a 5 km-long riffle and pool reach, with an average slope of 2.5 m/km (USGS 2000; Tualatin River Watershed Council (1999) reports the reaches slightly differently, with generally steeper gradients). Mean discharge is about 40 m^3/s. Flows are highest in the winter-to-spring period and lowest in summer and fall, with typically less than 3 percent of the

13 For example, this could occur if crabs entered the fish ladders, went through the diffuser gratings (which have openings about 2.5 cm wide and water velocities usually around 0.3 m/s), and became stranded, ultimately dying and clogging the screens. The screens are designed as the weakest link in the system, intended to blow out if they become clogged, but when they blow the ladder and sometimes the powerhouse must be shut down (Athearn pers. comm. 2001).

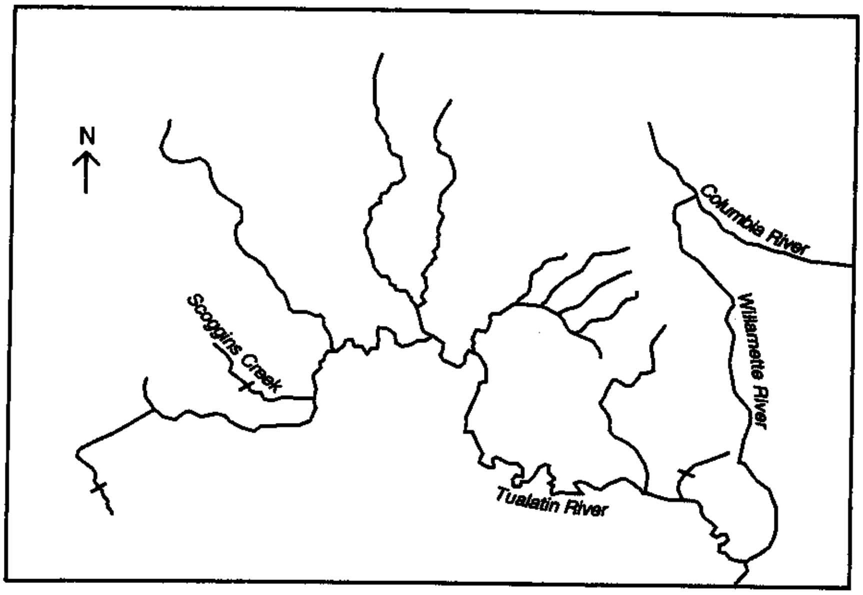

Figure 4. Tualatin River Basin

annual discharge occurring from June to October (Tualatin River Watershed Council 1999). Water is released from Henry Hagg Dam on Scoggins Creek to augment flows during the summer.

The temperatures in the lower Willamette River in June 1992 were 19.5-20.5°C, about 2°C higher than in the Columbia (Prahl *et al.* 1998), In the lower part of the Tualatin River temperatures are lowest in the late fall and winter and highest in the summer, often above 20°C. In Scoggins Creek and in the Tualatin River for some distance below the mouth of Scoggins Creek, summer releases from Henry Hagg Reservoir cool the water so that temperatures are lower in the summer than in the fall (Table 7). Four wastewater treatment plants discharge into the Tualatin River. Two of them dicharge during the summer low flow period, each releasing about 0.7 m^3/s of treated effluent into the river (USGS 2000). During the low flow period there are algal blooms followed by algal die-offs in the Tualatin, which result in periodic violations of State of Oregon standards for dissolved oxygen (minimum of 6 mg/l), pH (maximum of 8.5) and nuisance algal blooms (USGS 2000; Rounds *et al.* 1999). Dissolved oxygen concentrations may fall below 4 mg/l for short periods (Rounds *et al.* 1999).

USBR facilities. The USBR and a USBR partner, the Tualatin Valley Irrigation District, manage the Tualatin Project facilities on the Tualatin River and Scoggins Creek. The facilities include a dam and reservoir, two pumping plants and regulating tanks, and 153 km of lateral canals. Scoggins Dam is an earthfill dam on Scoggins Creek about 7 km from its mouth, with a structural height of 46 m and a height from stream bed to spillway crest of 27 m (USBR 2001). There is no fish ladder. The dam was built to impound water for irrigation and flood control in Henry Hagg Lake, which covers 4.6 km^2 and has a total capacity of 74 million m^3, (Risley & Doyle 1997; USBR 2001). The Patton Valley Pumping Plant and distribution system is located on Scoggins Creek about 4 km downstream of Scoggins Dam. The Spring Hill Pumping Plant and distribution system is located on the Tualatin River about 7 km below Scoggins Creek and 90 km from the mouth of the Tualatin (USBR 2001).

Barriers. Willamette Falls, a natural cascade about 12 meters high and 120 meters long, is located 43 km above the mouth of the Willamette River. There is a fish ladder carved into one side of the falls (Henry pers. comm. 1999), but most anadromous fish swim over the falls rather than use the ladder (Oregon PRD 1995; Wade pers. comm. 1999). The Willamette Falls Lock system, built in the 1870s and operated by the U.S. Army Corps of Engineers, allows boats to bypass the falls. There are four locks, each 12 m wide and 64 m long, with a total lift of 12.5 m. The locks were built in the 1870s, and are operated by the U.S. Army Corps of Engineers (USACE 1992; Dean Smith & Associates 1995). There are seven wood or metal barriers in the locks, which are opened an average of five to seven times a day, though sometimes five days may pass without their use (USACE 1992; Foster pers. comm. 1999).

The Lake Oswego Diversion Dam (also called Oregon Iron and Steel Dam), owned by the Lake Oswego Corporation, is 8 mi high and located about 6 km above the mouth of the Tualatin River. The dam impounds Lake Oswego, from which water is diverted into the Lake Oswego Canal, and has hydropower facilities. There is a fish ladder whose effectiveness varies with river flow, though the dam itself is passable to salmonids when the flashboards are down and flows are moderate. It is a short distance over a flat grassy area from one side of the dam to the other (ODFW 1990; Athearn pers. comm. 2001).

Suitability for mitten crabs. As discussed above, the estuary and lower reach of the Columbia River appear capable of supporting large mitten crab populations. Similarly, the lower Willamette and at least the lower portion of the Tualatin River appear to be good rearing habitat for mitten crabs. Temperatures in the upper portion of the Tualatin below Scoggins Creek may be somewhat low for good adult rearing, which requires temperatures of 15-30°C (Tables 5, 7 and 12).

Table 12. Range of daily water temperatures in the Tualatin River

		May-Nov, 1994	May-Nov, 1995
Distance above mouth:	95 km	5.7-17.4 °C	7.7-16.3 °C
	83 km	5.0-18.0 °C	6.9-18.3 °C
	62 km	5.1-19.3 °C	5.9-21.8 °C
	59 km	–	6.7-22.3 °C
	54 km	5.3-20.8 °C	–
	37 km	11.5-22.7 °C[a]	5.5-23.4 °C
	16 km	5.4-24.8 °C	8.2-23.4 °C

Data are from Risley & Doyle 1997.
[a] No data for November.

The two potential barriers below the USBR facilities may be passable to the crabs. Based on the large numbers of mitten crabs that migrate through low-lift locks in the rivers and canals of Europe, and their ability to climb submerged or exposed concrete walls several meters high, mitten crabs may well be able to make their way upstream past Willamette Falls through the Willamette Falls Locks, which have relatively short lifts. Crabs may also be able to make their way up the cascades. Once on the Tualatin River, crabs may be likely to climb over the Lake Oswego Diversion Dam or up its fish ladder, depending on flows and the setting of the flashboards, or bypass it on land.

The Spring Hill and Patton Valley pumping plants and distribution systems, and Scoggins Dam, are located 299-313 km above the mouth of the Columbia River. This is 224-238 km above the head of the estuary (as defined by the CREDDP; Simenstad *et al.* 1990) and 92-106 km above the reach of the tides. This is a long but not unattainable migration for large numbers of mitten crabs, based on observations in Europe of high crab densities 450 km from the mouth and 350 km above the head of the estuary of the Elbe River (Panning 1939). It thus seems possible that a large population of mitten crabs could spawn in the Columbia river estuary, find good rearing in the lower Columbia, Willamette and Tualatin rivers, and arrive in problematical numbers at the Tualatin Project facilities.

Columbia River System: (c) Yakima River

River characteristics. The Yakima River flows into the Columbia River 539 km from its mouth, above McNary Dam, the fourth dam on the river (Fig. 3). The Yakima is 345 km long with a 16,000 km^2 watershed (USEPA 2001). It includes a 119 km-long upper reach with a gradient of 2.7 m/km, a 53 km-long middle reach with a gradient of 2.1 m/km, and a 173 km-long lower reach with a gradient of 1.3 m/km (Morace *et al.* 1999). Most of the historic wetlands and flood plains have been eliminated by flood control dikes, agriculture or highway construction, substantially altering the river's hydrograph, and unnaturally low and high flows are now common (USBR 1998). Unregulated mean discharge is estimated to be about 160 m^3/s, and regulated mean discharge around 100 m^3/s, with a range of 60 to 1,300 m^3/s (USGS 2001). During the summer, about 75 percent of the flow in the lower river consists of agricultural return flow (USGS 2001). Water quality has been impaired throughout the basin (USBR 1998), and the river has some of the highest DDT concentrations in the nation (USEPA 2001).

USBR facilities. USBR's Yakima Project was built to supply water for irrigation. It includes six storage dams and reservoirs, a re-regulating dam, five diversion dams, thirty pumping plants, 670 km of canals, 2,966 km of lateral canals and drains, and two power plants (USBR 2001; Tables 13 and 14). In terms of river distance from the Columbia River, USBR structures range from Prosser Diversion Dam, the lowest at 76 km from the confluence, to Keecheelus Dam, over 300 km from the confluence.

Barriers. As described above, there are four large dams (Bonneville, The Dalles, John Day and McNary; Fig. 3 and Table 8) and reservoirs on the main stem of the Columbia River below the mouth of the Yakima River (USBR 2001). Each of these dams is equipped with fish ladders and navigation locks, and three of them have fish passage facilities for downstream migration of juvenile salmonids. Wanawish (Horn Rapids) Diversion Dam, a 1.5 m-high concrete weir, forms

Table 13. Dams of the Yakima Project

Dam	Watercourse	Dam Type	Structural Height (m)	Hydraulic Height (m)
Keechelus Dam	Yakima River	Earthfill	39	22
Cle Elum Dam	Cle Elum River	Earthfill	50	38
Kachess Dam	Kachess River	Earthfill	35	18
Bumping Lake Dam	Bumping River	Earthfill	19	11
Clear Creek Dam	North Fork Tieton River	Concrete Arch	26	17
Tieton Dam	Tieton River	Earthfill	97	60
French Canyon Dam	Cowiche Creek	Earthfill	23	17
Tieton Diversion Dam	Tieton River	Concrete Weir	1.5	0.9
Easton Diversion Dam	Yakima River	Concrete Weir	20.	13
Prosser Diversion Dam	Yakima River	Concrete Weir	2.7	2.1
Sunnyside Div. Dam	Yakima River	Concrete Weir	2.4	1.8
Roza Diversion Dam	Yakima River	Concrete Weir	20	10

Source: USBR 2001. See Table 8 for definitions of structural and hydraulic height.

Table 14. Reservoirs of the Yakima Project

Dam	Reservoir	Watershed Area (km^2)	Surface Area (km^2)	Active Capacity (10^6 m^3)
Keechelus Dam	Keechelus Lake	141	–	195
Cle Elum Dam	Cle Elum Lake	674	–	539
Kachess Dam	Kachess Lake	163	18	295
Bumping Lake Dam	Bumping Lake	176	–	42
Clear Creek Dam	Clear Lake	156	1	7
Tieton Dam	Rimrock Lake	485	–	244
French Canyon Dam	French Canyon Lake	41	–	0.8

Source: USBR 2001

the first obstacle on the Yakima, 28 km from its mouth. Further upstream, the lower USBR dams would create obstacles to reaching the structures higher on the river. However, most of the dams have fish ladders, and the earthfill storage dams typically have downstream faces with 2:1 slopes, which might be surmountable by mitten crabs.

Suitability for mitten crabs. As discussed above, the estuary and lower reach of the Columbia River appear capable of supporting large mitten crab populations. If large breeding populations do become established there, the Yakima Project would lie within easier reach than Grand Coulee Dam, and conditions in the lower Yakima River may provide suitable rearing habitat for mitten crabs. However, to reach the Yakima Project facilities—located at least 580-800 km above the mouth of the Columbia River, at least 500-720 km above the head of the estuary as defined by the CREDDP (Simenstad *et al.* 1990), and at least 240-560 km above the reach of the tides—would require considerably further upstream migration than has been reported for large numbers of mitten crabs in Europe (up to 450 km above the mouth and 350 km above the head of an estuary). The crabs would also have to pass the substantial obstacles posed by four large dams on the Columbia River, plus additional smaller dams as they migrated up the Yakima River Basin. It thus seems unlikely that significant numbers of crabs could reach the Project facilities.

Rogue River

Estuary characteristics. The Rogue River lies in southern Oregon, with its mouth at about 42.5°N latitude. The size of the estuary has been variously reported as <2 km^2 (NOAA 1998); as 2.5 km^2 at mean high tide (as measured by the Oregon Division of State Lands; Ratti 1979); and as 4.2 km^2 at mean high tide and 8.2 km^2 at highest high tide (Ratti 1979). It has an average depth of 3.3 m (NOAA 1998), with a minimum depth near the mouth of 7 m (Ratti 1979). This small estuary is dominated by river flows, with a mean discharge into the estuary of about 300 m^3/s, and mean monthly flows ranging from around 35 m^3/s in September to 460 m^3/s in January (Ratti 1979; NOAA 1998; Doff pers. comm. 2000). Salt water intrudes only a short distance from the mouth, ranging from negligible intrusion during high runoff to a normal maximum during low flows of 4.3 km, and a maximum of 5.8 km during the 1977 drought (Ratti 1979). Except during low flows, saline water is usually restricted to the lower 1.4 km^2 (Ratti 1979). In 1991-94, Wallace (1998) detected salt water in the estuary only in summer and early fall. The tidal range is1.5 m at the mouth and extreme flood tides can extend 7 km upstream (Ratti 1979; NOAA 1998). During summer the river inflow during a tidal cycle is about as large as the tidal prism, and during high flows it is many times greater.

Table 15. Some water temperature data for the Rogue River system

Location	Period	Mean	Range of Measures	References
Sea surface	Jan 1999	11.2°C	–	NOAA 1999
	Feb	10°C	–	Sverdrup *et al.* 1942
	Jul 1999	15.7°C	–	NOAA 1999
	Aug	14-15°C	–	Sverdrup *et al.* 1942
Estuary - surface temperature	Nov-Mar 1975-77	–	7.5-8.8°C	Confer pers. comm.
	Aug 1975-77	–	20.5-21.0°C	1998
Estuary - bottom temperature	Nov-Mar 1975-77	–	9.5-10.0°C	Confer pers. comm.
	Aug 1975-77	–	10.0-10.5°C	1998
River	July 1940-94	19°C	14-22°C	Silverside Outfitters
	Dec 1940-94	–	3-7°C	1999

Large river flows relative to estuary size can create large differences between bottom and surface water. In summer, bottom salinities in 1975-76 were 15-30 ppt while surface salinities remained below 10 ppt; in winter, bottom salinities ranged from 0-12 ppt while surface water was fresh; (Ratti 1979). Summer temperatures in the estuary average around 21°C at the surface and 10°C at the bottom, but were closer in the winter, averaging 8°C at the surface and 10°C at the bottom (Confer pers. comm. 1998) (Table 15). Sea surface temperatures off the mouth of the river are typically around 14-16°C in the summer and 10-11°C in the winter (Sverdrup *et al.* 1942; NOAA 1999).

There is very little shallow littoral area, and no tidal flats, marshes or submersed vegetation other than a few areas of sparsely vegetated intertidal gravel and beds of macroalgae attached to cobbles. Benthic organisms must either recolonize each summer, or tolerate strong currents, unstable gravel sediments and low salinity in the winter (Ratti 1979; NOAA 1998).

River characteristics. The Rogue River is a federal Wild and Scenic River. It has highly variable flows with numerous stretches of white water. The river is 346 km long, with a watershed of 13,000 km^2 (Ratti 1979). The gradient averages 2 m/km up to the first dam, Savage Rapids Diversion Dam, 168 km from the mouth of the river (Evanson pers. comm. 1999).

USBR facilities. There are three USBR projects in the Rogue River Basin. The Grants Pass Project includes Savage Rapids Diversion Dam on the mainstem of the Rogue River and associated pumping plants and canal system. The Rogue River Basin Project (Talent Division) includes seven storage and re-regulating dams, eleven diversion dams, canals and a power plant. The Bear Creek Project is located on Bear Creek, which flows into the Rogue River just above Gold Ray (or Gold Rey) Dam, which is owned by Jackson County. Numerous irrigation canals flow from Bear Creek into the surrounding countryside (Evanson pers. comm. 1999; Buettner pers. comm. 1999; USBR 2001). Dam and reservoir data are summarized in Tables 16-18.

Barriers. Savage Rapids Dam is a 12 m-high irrigation dam with two fish ladders, located at 168 km from the river mouth (USBR 2001). There is a 4-6 km long whitewater gorge below the dam. This dam is expected to be demolished in the next 10-40 years (Evanson pers. comm. 1999). Gold Ray Dam, just below the mouth of Bear Creek, was constructed for power generation but the power plant closed in the 1960s. The dam is about 6 m high with one fish ladder, which provides easier fish passage than the laders at Savage Rapids Dam. The facilities of the Rogue River and Bear Creek projects are located upstream of Gold Ray Dam.

Table 16. USBR storage dams in the Rogue River Basin

Dam	Watercourse	Dam Type	Structural Height (m)	Hydraulic Height (m)
Emigrant Dam	Emigrant Creek	earthfill	62	56
Howard Prairie Dam	Beaver Creek	earthfill	31	27
Agate Dam	Dry Creek	earthfill	26	21
Keene Creek Dam	Keene Creek	earthfill	24	18
Hyatt Dam	Keene Creek	earth- & rockfill	16	12
Fish Lake Dam	North Fork Little Butte Creek	earth- & rockfill	15	8.9
Fourmile Lake Dam	Fourmile Creek	rockfill	7.6	5.5

Source: USBR 2001. See Table 8 for definitions of structural and hydraulic height.

Table 17. USBR diversion dams in the Rogue River Basin

Dam	Watercourse	Dam Type	Structural Height (m)
Savage Rapids Diversion Dam	Rogue River	concrete arch, concrete gravity	11.9
Soda Creek Diversion Dam	Soda Creek	earthfill	4.0
Little Beaver Creek Diversion Dam	Little Beaver Creek	concrete core wall & rockfill	2.7
Antelope Creek Diversion Dam	Antelope Creek	stream drop inlet	2.2
Asland Lateral Diversion Dam	Emigrant Creek	concrete ogee weir, earth dike	1.5
Oak Street Diversion Dam	Bear Creek	concrete weir, stoplogged crest	1.5
Phoenix Canal Diversion Dam	Bear Creek	concrete weir, stoplogged crest	1.5
Beaver Dam Creek Diversion Dam	Beaver Dam Creek	concrete core wall	1.2
Conde Creek Diversion Dam	Conde Creek	concrete & rockfill weir	1.2
Daley Creek Diversion Dam	Daley Creek	rockfill, timber core wall	1.2
Dead Indian Creek Diversion Dam	Dead Indian Creek	concrete & rockfill weir	1.2
S Fork Little Butte Cr. Diversion Dam	S Fork Little Butte Creek	rockfill, timber core wall	1.2

Source: USBR 2001. See Table 8 for the definition of structural height.

Suitability for mitten crabs. The Rogue River estuary is very small compared to estuaries that have supported large numbers of mitten crabs (Table 11), with virtually no area of slow, shallow, vegetated water in the estuary or lower river to support juvenile and adult growth. The small brackish water area is especially reduced during the winter and spring when mitten crabs require access to brackish water. Surface temperatures within the estuary and off its mouth are within the range reported for watersheds with large mitten crab populations (Table 10), but the summer bottom temperatures in the estuary (about 10°C) are considerably below summer temperatures reported for estuaries with large mitten crab populations, and these low bottom temperatures persisting from winter through summer could retard egg development. The large river flows relative to the size of the estuary would likely flush a large portion of the larvae from the system. Thus the estuary and lower river do not appear capable of developing a substantial mitten crab population. Even if a modest population of mitten crabs were to become established in the estuary, they would be unlikely to arrive in significant numbers at the USBR facilities, which are all at least 160 km upstream from the head of the estuary.

Table 18. USBR reservoirs in the Rogue River Basin

Dam	Reservoir	Watershed Area (km^2)	Surface Area (km^2)	Active Capacity (10^6 m^3)	Total Capacity (10^6 m^3)
Savage Rapids Dam	–	6,374	0.6	–	3
Emigrant Dam	Emigrant Lake	166	3.3	48	50
Howard Prairie Dam	Howard Prairie Lake	205	7.7	74	77
Agate Dam	Agate Reservoir	34	0.9	6	6
Keene Creek Dam	Keene Cr. Reservoir	288	0.06	0.3	0.5
Hyatt Dam	Hyatt Reservoir	29	3.6	20	20
Fish Lake Dam	Fish Lake	52	1.7	10	10
Fourmile Lake Dam	Fourmile Lake	26	3.9	19	19

Source: USBR 2001

Klamath River

Estuary characteristics. The Klamath River drains a watershed of about 40,400 km^2 in southern Oregon and northern California, entering the ocean at around 41.5°N latitude. The estuary covers <2 km^2, and has an average depth of 7 m (NOAA 1998). Discharge into the estuary in 1991-94 ranged from 45 m^3/s in Aug 1994 to 3,830 m^3/s in March 1993 (Wallace 1998). In most years during winter and spring the estuary is thoroughly flushed by high river inflows, and conditions in the estuary resemble those in the lower river (Wallace 1998). Each year in late summer or early fall when river inflows are lowest, a sand berm forms at the mouth of the estuary. Though the berm rarely closes the mouth completely, it narrows it enough to substantially reduce tidal exchange, impound water and essentially create lagoon conditions (NOAA 1998; Wallace 1998).

Salinity is detectable in the estuary primarily in the summer and early fall, when the estuary is highly stratified. In 1991-94, the limit of detectable salinity during these months was typically 4 km upstream on the bottom at high tide, with a maximum in Sept 1991 of 6.4 km upstream. At low tide detectable salinity retreated to 1.6-3.2 km (Wallace 1998). Tidal influence normally extends about 6 km upstream (Wallace 1998).

Sea surface temperatures off the mouth of the estuary are typically around 10-13°C in the winter and 14-16°C in the summer (Sverdrup *et al.* 1942; NOAA 1999). Surface temperatures average 6-8°C in the winter and 17-23°C in the summer (Wallace 1998, Table 19). The estuary is typically vertically stratified in summer and fall, with temperatures about 5-8°C cooler on the bottom than at the surface (NOAA 1998; Wallace 1998).

River characteristics. Water velocities reach 3.0 m/s in the spring and drop to 0.3-1.5 m/s in the summer. The steepest gradient is at Ishi Pishi falls, which is a steep section of whitewater rather than a waterfall (Henrickson pers. comm. 1999).

Table 19. Some water temperature data for the Klamath River system

Location	Period	Mean	Range of Measures	References
Sea surface	Jan 1999	12.5°C	–	NOAA 1999
	Feb	10-11°C	–	Sverdrup *et al.* 1942
	Jul 1999	16.4°C	–	NOAA 1999
	Aug	14-15°C	–	Sverdrup *et al.* 1942
Mouth of estuary	Oct	–	13-15°C	NCRWQCB 1969
Just above tidal prism	Oct	15°C	–	NCRWQCB 1969
Estuary - surface temperature	Jun-Aug 1991-94	17-23°C	15-23°C	Wallace 1998
	Dec-Feb 1991-94	6-8°C	5.5-8.5°C	
Estuary - bottom temperature	Jun-Aug 1991-94	–	11.5-22°C	Wallace 1998
	Dec-Feb 1991-94	–	6-9.5°C	
Near Klamath	Apr-Sep	19°C	12-23°C	STORET 1999
	Oct-Mar	9°C	5-13.5°C	
Just upstream of estuary	1976-81	–	up to 26.5°C	Wallace 1998
	1991-94	–	up to 23.5°C	
Klamath River main stem	–	–	up to 26.6°C	Wallace 1998
Trinity River near Willow Creek	–	–	up to 25°C	Wallace 1998

USBR facilities. The Klamath Project, located near Klamath Falls at about 450 km from the mouth of the river, includes three storage dams, four diversion dams, three major pumping plants, 3 km of tunnels, 300 km of canals, 860 km of lateral canals and 1,170 km of drains (USBR 2001). The Project was built to provide irrigation water, and serves an area of over 9,100 km^2 (USBR 2001). The two main sources of water for the project are Upper Klamath Lake, regulated by Link River Dam, and the waters of the closed Lost River Basin, with the main impoundments formed by Clear Lake Dam and Gerber Dam (Tables 20 and 21).

Table 20. Dams of the Klamath Project

Dam	Watercourse	Dam Type	Structural Height (m)	Hydraulic Height (m)
Clear Lake Dam	Lost River	earth and rockfill	13	10
Gerber Dam	Miller Creek	concrete arch	27	19
Link River Dam	Link River	reinforced concrete slab	6.7	2.4
Lost River Diversion Dam	Lost River	concrete multiple-arch	13	7.9
Anderson-Rose Diversion Dam	Lost River	reinforced concrete slab	7.0	3.7
Malone Diversion Dam	Lost River	earth embankment	9.8	5.5
Miller Diversion Dam	Miller Creek	concrete weir	3.0	1.5

Source: USBR 2001. See Table 8 for definitions of structural and hydraulic height.

Table 21. Reservoirs of the Klamath Project

Dam	Reservoir	Watershed Area (km^2)	Surface Area (km^2)	Active Capacity (10^6 m^3)	Total Capacity (10^6 m^3)
Clear Lake Dam	Clear Lake Reservoir	1,900	104	633	650
Gerber Dam	Gerber Reservoir	600	15	116	116
Link River Dam	Upper Klamath Lake	9,900	368	646	>907

Source: USBR 2001

Barriers. Iron Gate Dam, 305 km upstream of the mouth of the river, is the first man-made barrier in the river. Copco Dam lies just upstream at 318 km from the mouth. The dams, owned by Pacific Power and Light, are 46 m and 61 m high with no fish ladders (Henrickson pers. comm. 1999).

Suitability for mitten crabs. Surface temperatures within the Klamath River estuary and in the coastal waters off its mouth are within the range reported for watersheds with large mitten crab populations (Table 10). However, like the Rogue River, the Klamath River estuary is very small compared to estuaries that have supported large numbers of mitten crabs (Table 11), and is completely flushed by river inflows from late fall to spring, virtually eliminating the area of brackish water needed for good egg and early larval development. The large river flows relative to the size of the estuary would also tend to flush larvae out of the system. Thus the estuary does not appear capable of supporting a substantial mitten crab population.

Even if a population of mitten crabs were to become established in the estuary, they would be unlikely to reach the USBR facilities in significant numbers. The distance from the estuary to the nearest USBR facilities is about 450 km. This is about or above the limit of upstream migrating distance reported for large numbers of mitten crabs in Europe (450 km above the mouth and 350 km above the head of an estuary), and would require the ascent of fast-flowing stretches of whitewater and passage around Iron Gate and Copco dams, both of which lack fish ladders.

<u>Sacramento-San Joaquin River System / San Francisco Bay</u>
Estuary characteristics. The San Francisco Bay estuary includes the inland freshwater Delta of the Sacramento and San Joaquin rivers and four saline embayments that make up San Francisco Bay: Suisun Bay and San Pablo Bay downstream from the Delta; the Central Bay which connects to the Pacific Ocean through an opening in the Coast Range at the Golden Gate; and the South Bay, a large shallow lobe extending off the Central Bay (Cohen 2000). The estuary's watershed covers 163,000 km^2, including more than 40% of the state of California, and the estuary, defined as the area within reach of the tides, covers about 1,240-1,520 km^2, with about 200 km^2 of tidal marsh and 250 km^2 of non-tidal marsh (Conomos 1979; Monroe & Kelly 1992; NOAA 1998; Cohen 2000). The tides are mixed semidiurnal, with the tide range varying from about 1.7 m at the estuary mouth to 2.6 m at the south end of the South Bay (Conomos 1979). Salinity typically intrudes to around the western Delta (Monroe & Kelly 1992). Tidal influence extends up the Sacramento River to above the city of Sacramento, and up the San Joaquin River past Stockton.

San Francisco Bay has extensive intertidal flats and shallow water, especially in the South Bay and San Pablo Bay, with a mean depth overall of about 6 m at Mean Lower Low Water, and typical channel depths of 10-20 m (Conomos 1979; Monroe & Kelly 1992; Cohen 2000). There are some seaweed beds, especially in the Central Bay and South Bay (Silva 1979; Josselyn & West 1985), and about 100 hectares of eelgrass beds (*Zostera marina*) (WESCO 1988). The Delta includes many slough and backwater areas and a few flooded shallow "islands"—areas that were originally marsh, then were diked off and farmed for decades, and then later inundated again.

Roughly 90 percent of the inflow to the estuary enters through the Delta, primarily from the Sacramento and San Joaquin rivers. Mean discharge into the estuary is usually estimated at around 1,000 m^3/s, with annual means ranging from around 300 to 3,000 m^3/s (Table 2). Sea surface temperatures off the mouth of the estuary are typically around 11-14°C in the winter and 14-17°C in the summer (Sverdrup *et al.* 1942; NOAA 1999), while temperatures in the Bay range from around 7-12°C in winter to 16-22°C in summer (Conomos 1979). Some temperature data for the watershed are provided in Table 22.

Table 22. Some water temperature data for the San Francisco Bay watershed

Location	Period	Mean	Range of Measures	References
Sea surface	Jan 1999	13.9°C	–	NOAA 1999
	Feb	11-12°C	–	Sverdrup *et al.* 1942
	Jul 1999	16.8°C	–	NOAA 1999
	Aug	14-15°C	–	Sverdrup *et al.* 1942
San Francisco Bay	winter	–	7-12°C	Conomos 1979
	summer	–	15-22°C	Conomos 1979Conomos 1979
– at the Golden Gate	mean monthly 1969-77	–	10-16°C	Conomos 1979
– at Alameda	mean monthly 1969-77	–	10-20°C	
Sacramento-San Joaquin Delta at Tracy	Mar 2000-Mar 2001	16.9°C	7.3-27.4°C	Craft *et al.* 2001
Sacramento River at Red Bluff Diversion Dam	Apr-Sep	14.6°C	–	STORET 1999[a]
	Oct-Mar	10.9°C	–	
Sacramento River at Keswick	Apr-Sep	11.1°C	–	STORET 1999[a]
	Oct-Mar	9.4°C	8-14.5°C	
American River at Nimbus Dam	Apr-Sep	17.5°C	10-19°C	STORET 1999[a]
	Oct-Mar	11.8°C	8.3-16.5°C	
San Joaquin River below Friant Dam	Apr-Sep	12.8°C	10-22°C	STORET 1999[a]
	Oct-Mar	10.4°C	8-14°C	
Tuolumne River at Modesto	Apr-Sep	21.8°C	–	STORET 1999[a]
	Oct-Mar	12.3°C	–	
Tuolumne River at La Grange Bridge	Apr-Sep	12.6°C	7-16°C	STORET 1999[a]
	Oct-Mar	11.8°C	8-16.3°C	

[a] Means and ranges of data in STORET database for 1980-1997.

USBR facilities. The USBR's Central Valley Project (CVP) ranges more than 650 kilometers north to south from the Cascade Mountains to the Tehachapi Mountains. Facilities in the San Francisco Bay watershed are located in the Sacramento River drainage to the north, the San Joaquin River drainage to the south, and the Delta region in the center where the two rivers join. There are also facilities in the Trinity River watershed (Trinity River Division) for collecting, storing and delivering water into the Sacramento River drainage, and facilities for delivering water to the central California coast (San Felipe Division). Facilities in the San Francisco Bay watershed include 20 dams and reservoirs, pumping plants, power plants, canals, pipelines, drains and other conduits, and fish passage, fish salvage and fish rearing facilities (Tables 23 and 24). Major

Table 23. Central Valley Project dams and reservoirs in the San Francisco Bay watershed

Dam	Structural Height (m)	Hydraulic Height (m)	Reservoir	Surface Area (km^2)	Total Capacity (10^6 m^3)
Shasta Dam	184	160	Shasta Lake	120	5,620
Whiskeytown Dam	86	77	Whiskeytown Lake	13	298
Keswick Dam	48	36	Keswick Reservoir	2.6	29
Spring Creek Debris Dam	60	52	Spring Creek Reservoir	0.4	7.0
Red Bluff Diversion Dam	16	6.4	Red Bluff Reservoir	2.1	4.8
Funks Dam	24	11	Funks Reservoir	–	–
Black Butte Dam	–	–	Black Butte Reservoir	18	197
Sly Park Dam	58	50	Jenkinson Lake	2.6	51
Folsom Dam	104	82	Folsom Lake	46	1,250
Nimbus Dam	27	14	Lake Natoma	2.2	11
Camp Creek Diversion Dam	6.1	3.4	–	–	–
Sugar Pine Dam	63	–	Sugar Pine Reservoir	0.7	7.8
Contra Loma Dam	33	25	Contra Loma Reservoir	0.3	2.6
Martinez Dam	19	13	Martinez Reservoir	0.06	0.3
B.F. Sisk (San Luis) Dam	116	92	San Luis Reservoir	53	2,520
O'Neill Forebay Dam	27	19	O'Neill Forebay	9.1	70
Little Panoche Detention Dam	46	26	Little Panoche Reservoir	0.8	6.9
Los Banos Detention Dam	51	38	Los Banos Reservoir	2.5	43
New Melones Dam	191	176	New Melones Lake	51	2,990
Friant Dam	97	89	Millerton Lake	20	643
John A. Franchi Diversion Dam	4.6	4.6	–	–	–

Source: California DWR 1983; USBR 2001. See Table 8 for definitions of structural and hydraulic height.

Table 24. Major canals of the Central Valley Project in the San Francisco Bay watershed

Canal	Region	Length (km)	Capacity (m^3/s)
Corning Canal	Sacramento Valley	34	14
Tehama-Colusa Canal	Sacramento Valley	182	72
Folsom-South Canal	Sacramento Valley	43	100
Contra Costa Canal	Delta	76	10
Delta-Mendota Canal	San Joaquin Valley	185	130
Friant-Kern Canal	San Joaquin Valley	242	113
Madera Canal	San Joaquin Valley	57	28
San Luis Canal	San Joaquin Valley	163	370

Source: California DWR 1983; USBR 2001

facilities are located on the Sacramento, American, San Joaquin and Stanislaus rivers and in the Delta. The San Luis Dam and Reservoir, the O'Neill Dam and Forebay, and associated facilities of San Luis Unit are jointly operated with the California State Water Project (SWP).

In the Sacramento River watershed, the CVP collects and stores water in Shasta Lake on the Sacramento River and Folsom Lake on the American River. Water from Trinity River is also collected, re-regulated and conveyed through a system of tunnels into the Sacramento River. Some CVP contractors divert water from the Sacramento and American Rivers. The remaining water is carried down the Sacramento River to the Sacramento-San Joaquin Delta. At the southern end of the Delta, the Tracy Pumping Plant lifts water into the Delta-Mendota Canal, which delivers it to contractors and exchange contractors on the San Joaquin River and the Mendota Pool. Some water is also pumped from the Delta-Mendota Canal into San Luis Reservoir for deliveries to contractors through the San Luis Canal and to contractors in Santa Clara and San Benito counties through the Pacheco Tunnel. Water is collected in New Melones Reservoir on the Stanislaus River for water rights holders in the Stanislaus River watershed and CVP contractors in northern San Joaquin Valley, and in the Millerton Lake on the San Joaquin River for contractors on the Madera and Friant-Kern canals.

Mitten crab distribution in the watershed. Mitten crabs were discovered in southern San Francisco Bay in 1992 (Cohen & Carlton 1997). By 1997 they had become abundant throughout the Bay and Delta region and were present in rivers and streams in the Central Valley. The highest densities of crabs have been reported within or not far upstream of the reach of the tides: in the South Bay and San Pablo Bay and their tributary creeks, in waterways in Suisun Marsh, and in the western Delta. The very large numbers of downstream migrating crabs collected at CVP and SWP pumps in the south Delta in 1998 indicate that crabs were also abundant in the San Joaquin River system upstream of the pumps. Lower densities have been reported in the Yolo Bypass and Sutter Bypass to the north of the Delta, and in Mormon Slough and Littlejohns Creek east of Stockton (Hieb & Veldhuizen 1998; Veldhuizen & Hieb 1998; Rudnick *et al.* 1999; Hieb pers. comm. 1999). Mitten crabs have been collected in the Sacramento River about 20 km upstream of Colusa (about 250 km from the river mouth at Chipps Island)and in the Feather River drainage above Marysville (Rudnick *et al.* 2000; Hieb pers. comm. 2001). In the San Joaquin River watershed they have been collected in the San Joaquin River near Merced, in the Delta-Mendota Canal south to Los Banos, and in the SWP's California Aqueduct south to near Bakersfield, a distance of about 400 km (Rudnick *et al.* 1999, 2000; Langlois pers. comm. 2001).

Barriers. Various water project facilities in the Delta and in the lower elevation portions of the Sacramento and San Joaquin valleys, such as flood control weirs in the lower Sacramento Valley, channel gates, and temporary rock barriers used to direct flows, may pose partial barriers to mitten crab migration, but these are generally low enough or in flat enough terrain that mitten crabs can climb over or walk around them. For example, in 1998 upstream migrating crabs climbed over or walked around weirs in the Sutter and Yolo bypasses, including the 2.7 m-high Sacramento Weir (Hieb & Veldhuizen 1998; Veldhuizen & Stanish 1999; Hymanson pers. comm. 1999).

It has been suggested that a "hydraulic barrier" may have redirected downstream crab migration in the Delta in 1999. In some years, rock barriers are placed in the Old River, Middle River and Grant Line Canal to manage water levels, water quality and flows for agriculture and for salmon migration. These barriers shunt San Joaquin River flow through the main stem of the San Joaquin River rather than through the Old and Middle Rivers, and thus away from the CVP and SWP pumping plants in the south Delta. These barriers were not in place in 1998 when thousands to tens of thousands of mitten crabs per day arrived at the CVP's Tracy Fish Collection Facility during the fall, with peak numbers of up to 40,000 crabs per day arriving during September. In 1999 the barriers were in place from May to early October, and the numbers of crabs at the facility were much smaller, with peak arrivals of about 4,000 crabs per day occurring after the barriers were removed in October. While the barriers themselves probably did not pose a significant physical obstacle to the crabs, crabs migrating down the San Joaquin River may have followed the main water flow as it was shunted around and away from the region of the pumps and fish screens (Hess pers. comm. 2000).

Suitability for mitten crabs. Mitten crabs have been abundant in parts of San Francisco Bay, the Delta and the lower San Joaquin River, arriving at the CVP and SWP fish screen facilities in the southern Delta at a rate of tens of thousands per day during their downstream migration in the late summer and fall of 1998. San Francisco Bay apparently provides good salinity and temperature regimes for reproduction and larval development, and both the Bay and the Delta, with large intertidal and shallow areas and many sloughs, flooded islands and other backwaters with shallow, productive waters, provide excellent rearing habitat. During years of mitten crab abundance, large numbers of mitten crabs could arrive at any of the USBR project facilities in the Delta.

On the Sacramento River, Red Bluff Diversion Dam is located 391 km upstream from the river mouth at Chipps Island, which is near the usual limit of saline water, and about 290 km from the upstream reach of the tides. This is on the order of the furthest upstream distance reported for large numbers of mitten crabs in Europe (450 km from the mouth and 350 km from the head of an estuary), although the furthest upstream collection of a mitten crab on the Sacramento River to date was about 140 km below Red Bluff Diversion Dam. Red Bluff Diversion Dam is a gated concrete weir with a hydraulic height with the gates closed of 6.4 m. The gates, however, are open for a substantial part of the year (Hymanson pers. comm. 2001), which considerably lessens the vertical distance that a crab would need to surmount. Crabs that reached Red Bluff Diversion Dam might be able to climb over it, ascend its fish ladders, or walk around it. Water from the settling basin at the dam passes through drum screens to the Tehama-Colusa Canal, which is thus within potential reach of mitten crabs if they can bypass the screens.

Further upstream on the Sacramento River, a diversion dam owned by the Anderson-Cottonwood Irrigation District and equipped with fish ladders is located 90 km above Red Bluff Diversion Dam, USBR's Keswick Dam is 6 km further, and USBR's Shasta Dam is another 14 km further. USBR's Whiskeytown Dam is located 27 km up Clear Creek, a tributary that enters the Sacramento River at around 470 km from its mouth. These USBR dams are about 480-500 km from the Sacramento river mouth at Chipps Island, and perhaps 380-400 km above the reach of the tides, which is a moderate distance beyond the furthest upstream range reported for large numbers of mitten crabs in Europe. While the distance and the two low diversion dams downstream (both equipped with fish ladders) should attenuate upstream migration, it may nonetheless be possible for significant numbers of mitten crabs to reach the more downstream of these USBR dams. Keswick Dam, a concrete gravity dam with a hydraulic height of 36 m and no fish ladder over it, would block any further progress up the Sacramento River toward Shasta Dam, although it would be possible for crabs to reach the salmon ladder and trap at the base of Keswick Dam (constructed by USBR and operated by the U.S. Fish and Wildlife Service). Whiskeytown Dam, a zoned earthfill dam with a hydraulic height of 77 m and no fish ladder, would likely block any further progress upstream on Clear Creek.

The American River enters the Sacramento River at 97 km from its mouth, at about the upstream limit of tidal influence. Nimbus Dam is located on the American River 37 km from its mouth, and Folsom Dam is 11 km further upstream. The Nimbus Fish Hatchery, 0.4 km below Nimbus Dam, was constructed by USBR and is operated by the State of California with USBR funds (USBR 2001). The American River from its mouth to the fish hatchery has been described in three reaches with gradients of 0.3 m/km in the lower 8 km reach, 0.5 m/km in the middle 11 km reach, and 0.8 m/km in the upper 18 km reach (Snider *et al.* 1992). Mitten crabs have been found in the American River up to around 14 km above its mouth (Veldhuizen pers. comm. 2001). Given the relatively short distance and low gradient from the estuary, large numbers of mitten crabs could reach the fish hatchery and Nimbus Dam. Although there is no fish ladder at Nimbus Dam, mitten crabs could possibly walk around the dam, which is surrounded by a flat grassy area, and enter Lake

Natoma and the Folsom-South Canal. Further upstream migration would be blocked by Folsom Dam, a concrete gravity dam with a hydraulic height of 82 m and no fish ladder (USBR 2001).

South of the Delta, mitten crabs have been reported from several sites in the Delta-Mendota Canal and the SWP's California Aqueduct. Crabs entering either of these conveyance facilities could potentially travel south with the flow of current by different routes to various regions, including traveling to San Luis Reservoir and through the Pacheco Tunnel to the USBR's San Felipe Division on the west side of the Coast Range, via the San Luis and Coalinga canals to the west side of the San Joaquin Valley, via the Delta-Mendota Canal to re-enter the San Joaquin River at Mendota Pool, or continuing south via the California Aqueduct to and possibly over the Tehachapi Mountains into the Los Angeles basin. For crabs to initially reach the Delta-Mendota Canal requires passage through the screens at the Tracy Fish Collection Facility, through the pumps at the Tracy Pumping Plant, and then a pumped ascent of 60 m, and, similarly, to reach the California Aqueduct requires passage through the John E. Skinner Fish Protective Facilities, the Harvey O. Banks Delta Pumping Plant and a pumped ascent of 74 m. That only a small number of crabs were found in the aqueduct systems beyond the pumps during a year when hundreds of thousands of crabs reached the CVP and SWP fish screens in the south Delta, suggests that the aqueduct systems are not likely to serve as migratory routes for large numbers of mitten crabs in the future (assuming that the fish screen facilities continue to operate and intercept crabs).

The Stanislaus River enters the San Joaquin River at about 120 km from its mouth at Chipps Island, and perhaps 40 km above the upstream limit of the tides. Going upstream on the Stanislaus River one encounters Goodwin Dam, Tulloch Dam and then New Melones Dam at about 96 km from the river's mouth. Goodwin Dam is a 24 m-high multi-arch concrete dam which impounds Goodwin Reservoir with a capacity of 0.6 x 106 m^3. Tulloch Dam is a 63 m-high concrete gravity dam, and impounds Tulloch Reservoir with a capacity of 84 x 106 m^3, which when full backs up to New Melones Dam. Goodwin and Tulloch dams are owned and operated by the Oakdale and South San Joaquin Irrigation districts (USBR 2001). There are no fish ladders on any of the three dams. Mitten crabs have been reported in the San Joaquin River upstream of the mouth of the Stanislaus River, but not in the Stanislaus River itself. Although New Melones Dam is within the upstream distance reported for large numbers of mitten crabs in Europe, mitten crabs are unlikely to make it past Goodwin or Tulloch dams.

Friant Dam is located on the San Joaquin River, about 270 km from its mouth and perhaps 190 km from the upstream limit of the tides. Mitten crabs have been reported in the San Joaquin River up to about 130 km below Friant Dam. Currently, the San Joaquin River below Friant Dam is inhospitable to mitten crabs, because water diversions dewater the river at the Gravelly Ford reach in late summer to early fall (Kondolf pers. comm. 1999). If year-round flows are restored, large numbers of mitten crabs could potentially colonize the river up to Friant Dam, and the dam lies within the upstream distance reported for large numbers of mitten crabs in Europe (450 km from the mouth and 350 km from the head of an estuary). Further progress upstream, however, would be blocked by Friant Dam, which is a concrete gravity dam with a hydraulic height of 89 m and no fish ladder.

Lavaca and Nueces Watersheds / Coastal Bend Estuaries

Estuary characteristics. The Lavaca River discharges into Matagorda Bay through Lavaca Bay, and the Nueces River discharges into Corpus Christi Bay through Nueces Bay. These bays, in turn, are part of the interconnected Texas Coastal Bend estuarine complex, which stretches from Matagorda Bay through San Antonio Bay, Aransas Bay, Corpus Christi Bay and the Laguna Madre. This complex of bays with associated marshes, sloughs, sea grass beds, oyster reefs and intertidal mud-sand flats runs for over 400 km and covers 4,900 km^2 behind a series of barrier islands (Corpus Christi Bay NEP1996; NOAA 1997; Texas SHA 1999). Openings to the Gulf of

Mexico include, from northeast to southwest, Brown Cedar Cut (East Matagorda Bay), Matagorda Ship Channel and Cavallo Pass (Matagorda Bay), Cedar Bayou (Mesquite Bay), Aransas Pass (Redfish Bay), Corpus Christi Pass (Corpus Christi Bay), and Brazos Santiago Pass (southern Laguna Madre). Major components and tributaries of this system are listed in Tables 25 and 26.

Table 25. Components of the Texas Coastal Bend Estuarine Complex

Estuary System	Component Embayments	Estuary Area (km^2)	Mean Mid-tide Depth (m)	Watershed Area[a] (km^2)	Mean Discharge (m^3/s)
Matagorda	East Matagorda Bay, Matagorda Bay, Tres Palacios Bay, Carancahua Bay, Lavaca Bay, Turtle Bay, Keller Bay, Cox Bay	1,140	2.1	15,300	117-177[b]
San Antonio	Espiritu Santo Bay, San Antonio Bay, Guadalupe Bay, Mission Lake, Hynes Bay, Ayres Bay, Mesquite Bay	557	1.3	4,030	91-116[b]
Aransas	Carlos Bay, Aransas Bay, Copano Bay, St. Charles Bay, Mission Bay, Port Bay	526	1.6	6,920	17-28[b]
Corpus Christi (Nueces Estuary)	Redfish Bay, Corpus Christi Bay, Nueces Bay, Oso Bay	538	2.4	5,060	23-34[b]
Laguna Madre	Upper Laguna Madre, Baffin Bay, Alazan Bay, Cayo Del Gruyo, Laguna Salada, Lower Laguna Madre, South Bay	2,140	0.8	14,000	18-26[b]
Coastal Bend Estuarine Complex		4,901	1.4	45,310	326-381

Data from NOAA 1997 unless otherwise stated.

a The watershed area given is "the land and water compnent of a watershed that drains into and most directly affects estuarine waters" (NOAA 1997).

b Range of means given in Corpus Christi Bay NEP 1996, NOAA 1997, USEPA 1999 and Texas WDB 2001.

The bays are shallow (with a mean depth at mid-tide of 1.4 m, ranging from 0.8 m in the Laguna Madre system to 2.4 m in the Corpus Christi Bay estuary), turbid and highly productive, with extensive intertidal habitat. Tide range is generally from 0.2-0.5 m (NOAA 1997). Mean salinities range from 13 ppt in the Aransas Bay estuary to 36 ppt in the Laguna Madre (Corpus Christi Bay NEP1996). Hypersaline conditions occur periodically in some of the estuaries, especially in the summer (Corpus Christi Bay NEP 1996; NOAA 1997). Salinities in San Antonio Bay and Aransas Bay estuaries typically do not exceed 35 ppt, and in Matagorda Bay and Corpus Christi Bay estuaries have historically exceeded 35 ppt for 1-8% of the year (Texas WDB 2001; Table 27). In contrast, the salinity in parts of the upper Laguna Madre has historically reached 50-60 ppt during droughts (Texas WDB 2001).

Winters in the region are mild with occasional freezes, and summers are hot and humid (Corpus Christi Bay NEP1996). Sea surface temperatures are typically around 19-22°C in the winter and around 28-29°C in the summer (Sverdrup *et al.* 1942; NOAA 1999; Table 28). In the bays and estuaries, temperatures normally range 8-16°C in February and 23-32°C in August to September. Summer temperatures occasionally exceed 35°C, especially in shallow areas with poor circulation or waters affected by return flows from power plants, with maximums around 37°C (Ward & Armstrong 1997; Texas A&M 2000).

Table 26. Main tributaries of the Texas Coastal Bend Estuarine Complex

Estuary System	Main Tributaries	Length (km)	Watershed Area (km^2)	Mean Discharge (m^3/s)
Matagorda	Colorado River	966	103,000	>78
	Lavaca River	185	5,900	23-30[a]
	– Navidad River[b]	119	–	–
San Antonio	Guadalupe River	406	15,700	–
	San Antonio River	290	–	–
Aransas	Copano Creek	39	–	–
	Mission River	39	–	–
	Aransas River	64	–	–
Corpus Christi	Nueces River	507	43,500	24
	– Frio River[c]	322	–	–
	Oso Creek	45	–	1-5[d]
Laguna Madre	Arroyo Colorado	84	–	–

Data from Texas SHA 1999, unless otherwise noted.
[a] Range of 5 estimates of mean discharge (USBR 1991).
[b] Tributary of the Lavaca River.
[c] Tributary of the Nueces River
[d] Range of annual means 1989-1993 (Baird *et al.* 1996).

Table 27. Some salinity data for the Texas Coastal Bend Estuarine Complex

Estuary System	Bay	Modal Salinity (ppt)	Percent of time that salinity exceeds 35 ppt
Matagorda	Matagorda Bay	20-25	2
	Lavaca Bay	10-15	1
San Antonio	Upper San Antonio Bay	0-5	0
	Middle San Antonio Bay	10-15	0
Aransas	Aransas Bay	15-20	0
	Copano Bay	10-15	0
Corpus Christi	Corpus Christi Bay	30-35	8
	Nueces Bay	25-30	6

Source: Texas WDB 2001.

Phytoplankton provide most of the primary productivity over much of the region, and there have been nuisance algal blooms in some parts of the system (Corpus Christi Bay NEP 1996; NOAA 1997). Phytoplankton produce about 52% of the annual carbon input to the Nueces Estuary, which ranges from 0.048 to 1.76 g/m^2/day (Corpus Christi Bay NEP 1996). Benthic infauna in the Nueces Estuary are most abundant in winter and spring, and are 2.5 to 7 times more abundant in lower, more marine sites than at upper estuary, freshwater sites. Mean secondary productivity rangeds from 0.96 g C/m^2/day at upper estuary sites to 1.30 g C/m^2/day at mid-estuary to 1.23 g C/m^2/day in the lower estuary (Corpus Christi Bay NEP 1996).

Table 28. Some water temperature data for the Texas Coastal Bend Estuarine Complex

Location	Period	Mean	Range of Measures	References
Sea surface	Jan 1999	18.5°C	–	NOAA 1999
	Feb	20-22°C	–	Sverdrup *et al.* 1942
	Jul 1999	28-29°C	–	NOAA 1999
	Aug	28-29°C	–	Sverdrup *et al.* 1942
Corpus Christi Bay	winter	14°C	–	Ward & Armstrong 1997
	summer	30°C	–	
Estuary	Feb	–	8-16°C	Texas A&M 2000
	May	–	23-28°C	
	Aug-Sep	–	23-32°C	

River characteristics. The lower reaches of the Lavaca and Nueces rivers flow across the South Texas coastal plain. Both are slow-moving rivers with marshes and oxbows, and are heavily forested with riparian vegetation. (USBR 1991; Irlbeck pers. comm. 1999).

USBR facilities. Facilities of the USBR's Palmetto Bend Project include Palmetto Bend Dam and its impoundment, Lake Texana. Tides reach to the base of the earthfill dam, which is located on the Navidad River about 6 km upstream from its confluence with the Lavaca River, and about 25 km from Lavaca Bay. The dam has a structural height of 28 m and a hydraulic height of 16 m. Lake Texana has a volume at conservation pool of 210 million m^3, a surface area of 45 km^2, a length of 29 km, an average depth of about 5 m and a maximum depth of 18 m. Operation and maintenance of the project has been transferred to the Lavaca-Navidad River Authority (USBR 1991, 2001; Irlbeck pers. comm. 1999).

Facilities of the USBR's Nueces Project include Choke Canyon Dam and Reservoir. The earthfill dam is located on the Frio River, a tributary of the Nueces River, about 150 km from the mouth of the Nueces River. It has a structural height of 43 m and a hydraulic height of 40 m, but a vertical distance between streambed and spillway crest of only 17 m. It is surrounded by gently sloping grassy areas (Irlbeck pers. comm. 1999; USBR 2001). The reservoir has a volume at conservation pool of about 860 million m^3, a surface area of about 140 km^2 and a length of 55 km. Operation and maintenance of the project has been transferred to the City of Corpus Christi and the Nueces River Authority (USBR 2001).

Barriers. There are no dams downstream of Palmetto Bend Dam, and two dams on the Nueces River downstream of Choke Canyon Dam. The Cal Allan Diversion Dam, owned by the City of Corpus Christi, is about 15 km upstream from the mouth of the Nueces River. This dam is about 1.4 m high and surrounded by a flat grassy area. Wesley E. Seale Dam, in the Lower Nueces River Water District, is about 45 km further upstream. This earthfill dam has a structural height of 24 m and impounds Lake Corpus Christi, which has a conservation surface area of 78 km^2 and storage capacity of 330 million m^3 (Texas SHA 1999; Irlbeck pers. comm. 2001; Martin pers. comm. 2001).

Suitability for mitten crabs. With some qualifications, the northern half of the Texas Coastal Bend estuarine complex appears suitable for colonization by mitten crabs and capable of supporting high abundances. The calm, shallow, highly productive waters of the various embayments in the Coastal Bend system, and some of the low gradient tributaries feeding into them, would in general appear to provide exceptional habitat for larval retention and development, and for juvenile and adult growth.

These embayments extend from about 26° to 29°N, with Matagorda Bay (with the Lavaca and Navidad rivers within its drainage) located at about 28.5°N and Corpus Christi Bay (with the Nueces and Frio rivers within its drainage) located at about 28°N. These bays lie within the latitude limits of the mitten crab in its native range, which is found south to about 24°N and is abundant in the Oujiang River at 28°N. Winter sea surface temperatures (at around 18-22°C) are considerably warmer than those for estuaries that have supported large numbers of mitten crabs (≤13°C), but winter estuary temperatures (8-16°C) are generally within the range for those estuaries (4-15°C). There is no evidence indicating that these winter temperatures are too high for mitten crabs, and they may be optimal (Table 5). Summer sea surface temperatures (28-29°C) and estuarine temperatures (23-32°C) are also near or above the temperatures for the warmest estuaries that have supported large numbers of mitten crabs (14-27°C and 16-25°C, respectively). There is some evidence that the upper end of the usual summer temperature range in the Coastal Bend estuaries (31-32°C) may be detrimental to mitten crabs, but most of that range would be optimal (Table 5 and accompanying text; note that estuarine temperature data are not available for the estuaries with abundant mitten crabs that have the coldest winter and warmest summer sea surface temperatures, so that the actual temperature range for estuaries with abundant mitten crabs is probably somewhat broader than indicated here). Some areas in the Coastal Bend estuaries with poor circulation or that receive return flows from power plants reach temperatures that would clearly be harmful to mitten crabs.

These embayments extend from about 26° to 29°N, with Matagorda Bay (with the Lavaca and Navidad rivers within its drainage) located at about 28.5°N and Corpus Christi Bay (with the Nueces and Frio rivers within its drainage) located at about 28°N. These bays lie within the latitude limits of the southernmost distribution of the crab in its native range, at about 24°N, and the southernmost mitten crab population center, in the Oujiang River at 28°N. Winter sea surface temperatures (at around 18-22°C) are considerably warmer than those for estuaries that have supported large numbers of mitten crabs (≤13°C), but winter estuary temperatures (8-16°C) are generally within the range for those estuaries (4-15°C). There is no evidence indicating that these winter temperatures are too high for mitten crabs, and they may be optimal (Table 5). Summer sea surface temperatures (28-29°C) and estuarine temperatures (23-32°C) are also near or above the temperatures for the warmest estuaries that have supported large numbers of mitten crabs (14-27°C and 16-25°C, respectively). There is some evidence that the upper end of the usual summer temperature range in the Coastal Bend estuaries (31-32°C) may be detrimental to mitten crabs, but most of that range would be optimal (Table 5 and accompanying text; note that estuarine temperature data are not available for the estuaries with abundant mitten crabs that have the coldest winter and warmest summer sea surface temperatures, so that the actual temperature range for estuaries with abundant mitten crabs is probably somewhat broader than indicated here). Some areas in the Coastal Bend estuaries with poor circulation or that receive return flows from power plants reach temperatures that would clearly be harmful to mitten crabs.

Hypersaline conditions also occur at times in the summer in some of the estuaries (Corpus Christi Bay NEP1996; NOAA 1997). Adult mitten crabs can apparently tolerate hypersaline conditions (Barrington 1979), at least temporarily. The available evidence does indicate, however, that brackish water is necessary for optimal development of early larval stages (Table 4 and accompanying text).

High summer temperatures and hypersaline conditions, as well as significant occurrences of anoxic conditions, are generally more typical of the Laguna Madre system, which constitutes the southern half of the Coastal Bend complex. Only about one percent of the surface area of the Laguna Madre system is classified as "mixing zone" or brackish water (0.5-25.0 ppt), and none is classified as tidal fresh water (0-0.5 ppt) (NOAA 1997, classification based on mean annual salinity throughout the water column). Average salinity is 36 ppt (USEPA 1999), which can increase to 45 ppt in the Lower Laguna Madre during periods of hot, dry weather (GEMS 2001). The Laguna Madre system therefore may not provide suitable conditions for mitten crab reproduction, egg development or larval development.

In contrast, 66 percent of the northern half of the Coastal Bend complex is classified as mixing zone or tidal freshwater, ranging from 9 percent of the Corpus Christi Bay estuary to 84 percent of the San Antonio Bay estuary (NOAA 1997). Average salinities range from 13 ppt in San Antonio Bay to 22 ppt in Corpus Christi Bay. Hypersaline conditions are much less common and of shorter duration than in the Laguna Madre (NOAA 1997). Thus the estuary systems at least from Matagorda Bay to Corpus Christi Bay, covering over 2,700 km^2, would appear to provide good conditions, and possibly near-optimal conditions, for mitten crab reproduction, development and growth.

The Palmetto Bend Project facilities are about 25 km upstream from the Lavaca Bay and are reached by the tides. The Nueces Project facilities are about 150 km upstream from Nueces Bay. These distances are within reach of upstream migrating mitten crabs, which in Europe have migrated as far as 450 km upriver in large numbers. The two small diversion dams downstream of the Nueces Project should not deter upstream migrating mitten crabs. The Wesley E. Seale Dam on the Nueces River, and the Palmetto Bend and Choke Canyon project dams, all earthfill dams surrounded by terrain of modest steepness, may pose only partial barriers to progress upstream.

Types of Potential Impacts

The concerns regarding mitten crabs can be organized into seven general categories:

<u>Vector for parasites</u>
Crabs in the genus *Eriocheir*, including *E. sinensis*, have been reported as a main vector for the transmission of a human parasite, the oriental lung fluke *Paragonimus westermani* (e.g. Chandler & Read 1961; Ingle 1986; California DFG 1986; USFWS 1988; Noble *et al.* 1989; Halat 1996; Cohen & Carlton 1997; Veldhuizen & Stanish 1999; Walter & Culver 2000). *P. westermani* has not been found in mitten crabs in North America (Walter & Culver 2000). However, high rates of human infection have been reported in the past from Asia (Chandler & Read 1961; Noble *et al.* 1989), and other mammals that consume mitten crabs can also be infected (USFWS 1988; Walter & Culver 2000). Two species of snails that have been reported to serve as second intermediate hosts in Asia (Chandler & Read 1961; Page 1973) have been introduced to Florida, Texas and/or Arizona (Burch 1989), and it may be possible for common, related native snails to also serve as second intermediate hosts (Gosliner pers. comm. 1994). Transmission to humans is via the consumption of uncooked or inadequately cooked crabs, which could limit the rate of infection even if the parasite became established in North America. Moreover, some Chinese experts have categorically stated that *P. westermani* is not found in mitten crabs even in Asia, but rather is carried only by crabs in entirely different families (Hymanson *et al.* 1999; Zhao presentation 1999; Zhang pers. comm. 1999).

<u>Damage to banks or levees</u>
There have been concerns raised that the burrowing activities of mitten crabs may weaken or undermine river banks, levees, dams, ditch walls or rice-field berms (California DFG 1986; USFWS 1988; Halat 1996; Veldhuizen & Stanish 1999; Rudnick *et al.* 1999, 2000). Mitten crabs appear to only burrow into banks in intertidal areas, primarily in competent clayey banks or in banks held together by plant roots, and perhaps mainly in shallow creeks (Peters 1933; Elton 1936; Halat 1996; Rudnick *et al.* 1999, 2000), though they sometimes burrow into the stream bottom in nontidal freshwater reaches (Halat 1996; Rudnick *et al.* 1999, 2000). Their burrows can be very

abundant, extending at a slight downward angle as far as 80 cm into the bank, although 20-60 cm is more typical, and ranging from 2-12 cm in diameter with 3-5 cm being typical (Peters 1933; Elton 1936; Halat 1996; Jiang pers. comm. 1998; Rudnick *et al.* 1999, 2000). Burrows under riprap on banks have been noted in Germany (Peters 1933) but not in China (Hymanson *et al.* 1999). Where submerged aquatic vegetation is abundant, mitten crabs will use it for cover rather than burrow (Veldhuizen 2000). Despite frequent general references in the scientific and gray literature to damage caused by mitten crab burrows in Europe (e.g. Panning 1939; Christiansen 1969; Ingle & Andrews 1976; Ingle 1986; Vincent 1996; Halat 1996; Cohen & Carlton 1997; Gollasch 1999; Veldhuizen & Stanish 1999; Rudnick *et al.* 1999, 2000), we were unable to find documentation or verbal accounts of a single specific instance in which levee failure had been attributed to mitten crabs. The only specific information that we found on bank erosion is from Peters (1933), who noted that substantial bank destruction apparently caused by mitten crabs, on the order of 1-2 m of bank retreat, seldom occurred in Germany.

Impacts on agriculture

Mitten crabs are frequently found in coastal rice fields in Asia (Ingle & Andrews 1976; Ingle 1986), and eat rice shoots (Ng 1988, cited in Halat 1996; Jiang pers. comm. 1998; Hymanson *et al.* 1999). Concern has been raised about potential damage to rice crops in the San Francisco Bay watershed. In China, mitten crabs are intentionally seeded into rice fields (Hymanson *et al.* 1999), since the crabs generally are a more valuable product than the rice consumed by them. The crabs may even enhance rice production by controlling herbivorous aquatic insects and by fertilizing the rice fields with their fecal pellets (Hess pers. comm. 2001).

Impacts on populations of native or fishery organisms

Concerns have been raised about the potential impacts of large numbers of mitten crabs on the ecosystems they invade (California DFG 1986; USFWS 1988; Cohen & Carlton 1997; Veldhuizen & Stanish 1999). There appears to be no documentation of any such impacts either in Europe (which is somewhat surprising given the scale of the invasion in the 1930s) or in Asia (which is less surprising, given that the interest there is primarily in raising them for the market). Significant impacts through predation seem unlikely as mitten crabs appear to primarily feed on detritus or vegetation with some consumption of invertebrates and dead fish (Elton 1936; Thiel 1937; Halat 1996; Rudnick *et al.* 1999, 2000; Veldhuizen 2000). Specific concerns that have been raised in the San Francisco Bay watershed include the possibility of impacts through predation on salmonid young or fry, which seems unlikely (Hymanson *et al.* 1999; Hess pers. comm. 2001),[14] consumption of aquatic insects that are important components of salmon diets (Hess pers. comm. 2001), predation on eggs of other fish that produce demersal or adhesive eggs (Veldhuizen & Stanish 1999), and predation on an endangered freshwater shrimp, *Syncaris pacifica* (Rudnick *et al.* 2000).

There has been some concern that mitten crabs may affect populations of exotic crayfish in the San Francisco Bay watershed through competition, including the red swamp crayfish *Procambarus clarkii*, and the signal crayfish *Pastifastacus leniusculus*, which supports a small commercial fishery (Halat 1996; Veldhuizen & Stanish 1999; Rudnick *et al.* 1999, 2000). Analyses of stomach contents showed that the mitten crab and red swamp crayfish have similar diets (Halat 1996; Rudnick *et al.* 1999, 2000), observations showed mitten crabs dominating red swamp crayfish when competing for food (Halat 1996; Rudnick *et al.* 1999, 2000), and experiments showed mitten crabs dominating signal crayfish when competing for shelter (Rudnick *et al.* 1999, 2000). However, site surveys produced no evidence that mitten crabs affect the distribution or abundance of red swamp crayfish (Halat 1996; Rudnick *et al.* 1999, 2000), and a survey of commercial crayfishermen produced no evidence that mitten crabs were having a harmful impact on signal crayfish (Rudnick *et al.* 1999, 2000). There are no native crayfish in the portions of the San

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[14] As noted above (Footnote 1), mitten crabs apparently do not capture and eat live fish, except as they may find injured fish or fish that are caught and disabled in nets or traps. Mitten crabs have also not been found in the upstream, higher gradient, gravel-bottom reaches where salmonids construct their redds, and may not invade these areas in large numbers (Hess pers. comm. 2001).

Francisco Bay watershed that have been invaded or are likely to be invaded by mitten crabs. The possibility of impacts on crayfish could become of greater concern if mitten crabs were to become abundant in watersheds with native crayfish, particularly rare or endangered crayfish.

Interference with fishing

Mitten crabs have at times been a substantial or major nuisance to the trap and set-net fisheries in Europe, and a minor nuisance to bottom trawl fisheries in Europe and San Francisco Bay, by clogging traps, clogging and sometimes damaging nets, and eating or damaging fish caught in traps or nets (Panning 1939; Christiansen 1969; Ingle & Andrews 1976; Vincent 1996; Gollasch 1999; Halat 1996; Veldhuizen & Stanish 1999; Rudnick *et al.* 1999, 2000). Mitten crabs have also been a modest nuisance to bait fishing in the San Francisco Bay watershed, by stealing bait (Veldhuizen & Stanish 1999).

Interference with fish salvage operations or fish passage facilities

The arrival of large numbers of downstream migrating mitten crabs caused major problems at the state and federal fish salvage facilities in the southern Sacramento-San Joaquin delta in the fall of 1998. The crabs clogged fish screens, entered fish bypass channels, collection devices and holding tanks, and were transferred into fish transport trucks in large numbers along with salvage fish (Siegfried pers. comm. 1998; Hess pers. comm. 1998; Siegfried 1999; Veldhuizen & Stanish 1999; Rudnick *et al.* 1999 , 2000). Salvage activities were hampered, requiring substantial additional work by salvage crews and other costs. Fish mortality was high, due to crabs interfering with the flushing of fish from holding tanks to the transfer bucket, from the transfer bucket to the transport truck, and from the transport truck into the river. At each of these stages the mass of crab bodies around the outlets allowed the water to drain out but not the fish. Experiments indicated that in certain circumstances large numbers of crabs in confined spaces could also reduce dissolved oxygen to harmful levels (Parker & Arnold 1999), though aeration or oxygenation of holding tanks and transport trucks apparently prevented this for happening at the delta fish salvage facilities (Hess pers. comm. 2001). Contact by fish with the sharp edges of crab carapaces in confined spaces could also remove scales and cause abrasions, potentially causing longer term mortality.

A crab trap and pump were temporarily installed at the USBR's Tracy Fish Collection Facility in 1998, and a travelling screen was subsequently designed and installed to help with removal of mitten crabs (Siegfried 1999; Wynn *et al.* 1999a, 1999b). These devices appeared to work, but because mitten crabs were less abundant at the facilities in subsequent years, the equipment has not been fully put to the test. Based on this experience, there are concerns about the potential effect of mitten crabs on fish passage or salvage facilities elsewhere, especially those designed for anadromous salmonids. These could include impacts on fish ladders and fish locks, on downstream juvenile fish passage systems, on fish collection systems and in the trucks and barges used to transport fish.

Clogging debris screens, valves, pipes, etc.

In addition to the operational problems at the fish salvage facilities, mitten crabs or their shells have clogged intake screens, pipes, condensers or valves at one wastewater treatment plant and two power plants in California, reducing power plant cooling flows on at least one occasion (Bauman pers. comm. 1996; Hieb pers. comm. 1997; Fagindo pers. comm. 1998; Veldhuizen & Stanish 1999). They have also been reported on intake screens at power plants in England (Andrews *et al.* 1982; Attrill & Thomas 1996; Clark *et al.* 1998). At the USBR's Tracy Fish Collection Facility, aside from interfering with fish salvage operations, on one occasion in 1998 an accumulation of mitten crabs and vegetative debris clogged the trash racks causing a 3-4 foot head across them (Brown 1998; Hess pers. comm. 2001). Although in a few of these cases there was a potential for significant damage, the actual problems caused by the clogging of screens, pipes and valves by mitten crabs have been minor.

Summary and Conclusions

Habitat Requirements

Some of the factors necessary for the establishment of mitten crabs and suitable for supporting an abundant population can be inferred from the available laboratory and field data and from the existing and historic distribution of mitten crabs. The necessary and optimal salinity and temperature ranges differ for different life stages, with the available data on these ranges summarized in Tables 4 and 5. Reproduction and embryonic and larval development apparently require brackish water, with optimal salinities in the range of 15-25 ppt and some indication of possible upper limits in the range of 25-35 ppt, with a possible preference for increasing salinities as zoeae develop. Megalopae can enter fresh water, and juvenile and adult growth and the initiation of gonadal development typically take place in fresh water. In laboratory experiments larvae required temperatures of at least 12°C, and good recruitment is obtained with estuarine temperatures of around 15-25°C in the spring and summer. Juveniles and adults can tolerate temperatures of around 4° to 31-32°C, and have behavioral adaptations that allow them to survive in systems where surface waters drop to around 0°C. Good juvenile and adult growth requires temperatures of around 15-30°C. Salinity and temperature ranges are not fully independent—larval salinity ranges, for example, broaden with increasing temperature.

While breeding populations of mitten crabs are present in some small coastal streams, large populations have occurred only in large rivers and estuaries (watersheds over 12,000 km^2, estuaries over 200 km^2, and mean discharge to the estuary of at least 100 m^3/s), with extensive shallow areas in the lower river and estuary with submerged vegetation. This is presumably because such systems provide both a large estuarine area with the persistent, intermediate salinities needed for larval retention and development, and large areas with high benthic primary productivity to sustain juvenile and adult growth.

Large mitten crab populations have occurred over a fairly broad latitude range, 28-41°N in Asia and 39-54°N in Europe. Latitudinal range limits might be set by water temperature; by poleward declines in freshwater primary productivity; or perhaps by other factors, such as competition with an increasing diversity of river crabs at southern range limits in Asia. It has been suggested by different researchers that pollution has either limited or enhanced mitten crab populations, but there appear to be no studies or compelling data on this point.

Mitten crabs are impressive climbers and can travel some distance overland. They can thus pass over or around some significant obstacles during their upstream migrations, including vertical dams or locks up to at least a few meters in height. While mitten crabs (in generally poor condition) were prevented from moving upstream by flows of 0.3 in a flume with a very smooth bed, and by flows over 0.55-0.60 m/s in a flume with a concrete bed, they are reported to migrate upstream in rivers with flows up to at least 1.5 m/s. It is thus unclear whether mitten crabs in substantial numbers could or could not ascend long fish ladders with water velocities between pools of 2-3 m/s, and their upstream distribution in some important western U.S. water systems may hinge on this.

There are no landlocked populations of mitten crabs, and it is not known whether they could survive or reproduce in inland waters with ionic ratios that differ from those of seawater.

Suitability of Estuarine/River Systems for Mitten Crabs

We examined five estuary systems in western North America that have USBR facilities in their watersheds. The Rogue River and Klamath River estuaries are very small compared to estuaries that have supported large mitten crab populations, and are flushed by river flows from late fall to spring. They provide neither a large area of estuarine brackish water for embryonic and larval development and larval retention, nor large areas of shallow, productive water for juvenile and adult growth, and thus not appear capable of supporting significant mitten crab populations.

The other three estuaries examined all appear to provide good habitat capable of supporting large mitten crab populations. Large expanses of good reproductive and rearing habitat are available in the Columbia River estuary and lower Columbia River and the lower portions of the Willamette and Tualatin rivers; in San Francisco Bay, the Sacramento-San Joaquin Delta, and the lower elevation portions of the Sacramento and San Joaquin river systems in California's Central Valley; and in at least the northern portion of the Texas Coastal Bend estuaries, from Matagorda Bay to Corpus Christi Bay.

Potential Spread Upstream

In the Columbia River watershed, mitten crabs are very unlikely to reach the USBR facilities on the Yakima River or on the main stem of the Columbia River at Grand Coulee Dam in significant numbers, but could reach the Tualatin Project facilities on Tualatin River and Scoggins Creek. USBR project operations in each of these upper portions of the watershed might be indirectly affected if an abundant mitten crab population in the estuary and lower river harmed anadromous salmonid populations through impacts on habitat or food resources, or by affecting fish passage or transport at the lower dams on the main stem of the river.

In the San Francisco Bay watershed, mitten crabs could not surmount lower dams to reach the USBR facilities at New Melones Dam in the Stanislaus River. They could possibly migrate as far as the base of Keswick Dam and Whiskeytown Dam in the upper Sacramento River watershed, and the base of Friant Dam on the San Joaquin River, though distance and various obstacles may prevent substantial numbers from making the migration. It appears possible for large numbers of mitten crabs to reach USBR project facilities throughout the Delta and up the American River at least as far as Nimbus Dam, and probably as far as the base of Folsom Dam. While a few crabs may be transported long distances by the USBR and California State Water Project conveyance systems that take water from the south Delta, these conveyance facilities are unlikely to be effective migration routes for large numbers of crabs.

In the Texas Coastal Bend region, both Palmetto Bend Dam on the Navidad River and Choke Canyon Dam on the Frio River would be within reach of large numbers of mitten crabs if a substantial population became established in the estuaries, and crabs may be able to migrate around or over these dams.

Potential Impacts

If mitten crabs should arrive at USBR facilities in substantial numbers, the main impacts likely to be relevant to project operations would be the potential for interference with fish passage facilities or fish salvage operations, and the potential for mitten crabs or their shells to clog screens, pipes or valves. Such clogging could potentially produce heads that cause the failure of system components, thereby disrupting fish transport, power generation or other activities.

References

Literature Cited

Andrews, M.J., K.F.A. Aston, D.G. Rickard and J.E.C. Steel. 1982. The macrofauna of the Thames Estuary. *Lond. Naturalist* 61: 30-61.

Anger, K. 1990. Der Lebenszyklus der Chinesischen Wollhandkrabbe (*Eriocheir sinensis*) in Norddeutschland: Gegenwärtiger Stand des Wissens und neue Untersuchungen ["Lifecycle of the Chinese mitten crab (*Eriocheir sinensis*) in northern Germany: update of knowledge and most recent investigations"]. *Seevogel, Zeitscrift Verein Jordsand Hamburg* 11(2): 32-36. [in German]

Anger, K. 1991. Effects of temperature and salinity on the larval development of the Chinese Mitten Crab *Eriocheir sinensis* (Decapoda:Grapsidae). *Mar. Ecol. Prog. Ser.* 72: 103-110.

Attrill, M.J. and R.M. Thomas. 1996. Long-term distribution patterns of mobile estuarine invertebrates (Ctenophora, Cnidaria, Crustacea: Decapoda) in relation to hydrological parameters. *Mar. Ecol. Prog. Ser.* 143: 25-36.

Baird, F.C., T.J. Dybala, M. Jennings and D.J. Ockerman. 1996. Characterization of Nonpoint Sources and Loadings to Corpus Christi Bay National Estuary Program Study Area. CCBNEP Rep. no. 05, Corpus Christi Bay National Estuary Program. [http://tarpon.tamucc.edu/]

Baker, P., S. Baker and R. Mann. 1994. Potential Range of the Zebra Mussel, *Dreissena polymorpha*, in and near Virginia. School of Marine Science, College of William and Mary, Gloucester Point, VA.

Barrington, E.J.W. 1979. Invertebrate Structure and Function. Second Edition. John Wiley & Sons, New York.

Bottom, D.L. and K.K. Jones. 1990. Species composition, distribution, and invertebrate prey of fish assemblages in the Columbia River Estuary. *Prog. Oceanog.* 243-270.

Bridges, B. 2001. Chinese mitten crab trapping program at the Tracy Fish Collection Facility. Chapter 3 in: 1998 Mitten Crabs at the Tracy Fish Collection Facility, Hess, L. (ed.), Tracy Fish Collection Facility Studies, U.S. Bureau of Reclamation, Mid-Pacific Region and the Technical Service Center (in press).

Brown, R. 1998. Mitten crabs. *Interagency Ecological Program Newsletter* (California Department of Water Resources, Sacramento, CA) 11(4): 4.

Buhk, F. 1938. Zur Fortpflanzungsbiologie der Wollhandkrabbe ["On the reproductive biology of the mitten crab"]. *Woschenschrift für Aquarien- und Terrarienkunde* 35(49): 776-780. [in German]

Burch, J.B. 1989. North American Freshwater Snails. Malacological Publications, Hamburg, MI.

Cabral, H.N. and M.J. Costa. 1999. On the occurrence of the Chinese Mitten Crab, *Eriocheir sinensis*, in Portugal. *Crustaceana* 72(1): 55-58.

California DFG. 1986. Pre-publication of Notice Supporting Placement of the Genus *Eriocheir* on the Department of Fish and Game Commission's List of Prohibited Species (June 12, 1986). California Department of Fish and Game, Sacramento, CA.

California DWR. 1983. The California Water Plan: Projected Use and Available Water Supplies to 2010. Bulletin 160-83, California Department of Water Resources, Sacramento, CA.

Carlton, J.T. and A.N. Cohen. 2001. Episodic global dispersal in shallow water marine organisms: The case history of the European shore crabs *Carcinus maenas* and *Carcinus aestuarii*. *J. Biogeogr.* (in press).

Castel, J. 1993. Long-term distribution of zooplankton in the Gironde Estuary and its relation with river flow and suspended sediment. *Cahiers de Biologie Marine* 34: 145-163.

Castel, J. 1995. Long-term changes in the population of *Eurytemora affinis* (Copepoda, Calanoida) in the Gironde Estuary (1978-1992). *Hydrobiologia* 311: 85-101.

Chan, T.Y., M.S. Hung, and H.P. Yu. 1995. Identity of *Eriocheir recta* (Stimpson, 1858) (Decapoda: Brachyura), with description of a new mitten crab from Taiwan. *J. Crust. Biol.* 15(2): 301-308.

Chandler, A.C. and C.P. Read. 1961. Introduction to Parasitology (10th Edition). John Wiley & Sons, New York.

Chelan County PUD. 2001. Chelan County (Washington) Public Utility District Website. [http://www.chelan.org]

Christiansen, M.E. 1969. Crustacea Decapoda Brachyura. Marine Invertebrates of Scandinavia, Vol. 2. Universitetsforlaget, Oslo, Norway.

Christiansen, M.E. 1977. Kinesisk ullhåndkrabbe funnet for første gang i Norge ["Chinese mitten crab found for the first time in Norway"]. *Fauna* 30: 134-138. [in Norwegian]

Christiansen, M.E. 1988. ["Second record of the Chinese mitten crab, Eriocheir sinensis, from Norway"] *Fauna (Oslo)* 41(1): 42. [in Norwegian]

Clark, P. 1984. Recent records of alien crabs in Britain. *Naturalist* (London) 109(970): 111-112.

Clark, P.F., P.S. Rainbow, R.S. Robbins, B. Smith, W.E. Yeomans, M. Thomas and G. Dobson. 1998. The alien Chinese Mitten Crab, *Eriocheir sinensis* (Crustacea: Decapoda: Brachyura), in the Thames catchment. *J. Mar. Biol. Ass. U.K.* 78: 1215-1221.

Clout, H.D. 2001. Weser River. Discovery Channel School, World Book Online, [http://www.discoveryschool.com/homeworkhelp/worldbook/atozgeography/w/598340.html]

Cohen, A.N. 2000. An Introduction to the San Francisco Estuary (3rd Edition). Save the Bay, Oakland, CA; San Francisco Estuary Project, Oakland, CA; and San Francisco Estuary Institute, Richmond, CA.

Cohen, A.N. and J.T. Carlton 1997. Transoceanic transport mechanisms: introduction of the Chinese mitten crab, *Eriocheir sinensis*, to California. *Pacific Science* 51(1): 1-11.

Cohen, A.N., A. Meinesz, D. Simberloff and others. 1998. Letter to Bruce Babbitt, Secretary, U.S. Department of the Interior, Washington, DC, October 19, 1998.

Cohen, A.N. and A. Weinstein. 1998. The Potential Distribution and Abundance of Zebra Mussels in California. A report for CALFED and the California Urban Water Agencies. San Francisco Estuary Institute, Richmond, CA.

Cohen, A.N. and A. Weinstein. 2001. Zebra Mussel's Calcium Threshold and Implications for its Potential Distribution in North America. A report for the Department of Energy, National Energy Technology Center, Morgantown, WV and California Sea Grant College Program, La Jolla, CA.

Conomos, T.J. 1979. Properties and circulation of San Francisco Bay waters. Pages 47-84 in: San Francisco Bay: The Urbanized Estuary, Conomos, T.J., A.E. Leviton and M. Berson (eds.), Pacific Division of the American Association for the Advancement of Science, San Francisco.

Corpus Christi Bay NEP. 1996. Current Status and Historical Trends of the Estuarine Living Resources Within the Corpus Christi Bay National Estuary Program Study Area, Volume 3: Project Summary. Report CCBNEP-06C, Corpus Christi Bay National Estuary Program, Texas A&M University, Corpus Christi, TX. [http://tarpon.tamucc.edu]

Craft, D., R. Housewright, L. Mao and J. Fields. 2001. Continuous Water Quality Monitoring at the Tracy Fish Collection Facility: March 2000 through March 2001. Tracy Fish Collection Facility Studies, Volume 19, U.S. Bureau of Reclamation, Denver, CO (in press).

Dai, A-Y. 1988. ["A preliminary cladistic analysis on *Eriocheir* (Crustacea: Decapoda)"]. *Acta Zootaxonomica Sinica* 13(1): 22-26. [in Chinese]

Dai, A-Y. 1991. ["Studies on the subspecies differentiation of the genus *Eriocheir* (Decapoda: Brachyura)"]. *Scientific Treatise on Systematic and Evolutionary Zoology* 1: 61-71. [in Chinese]

Dai, A. and S. Yang. 1991. Crabs of the China Seas. China Ocean Press, Beijing.

Dean Smith & Associates. 1995. Willamette River Recreation Guide. Oregon State Marine Board and Oregon Parks and Recreation Department, Portland, OR.

De Jong, D.J. and V.N. de Jonge. 1995. Dynamics and distribution of microphytobenthic chlorophyll-*a* in the Western Scheldt estuary (SW Netherlands). *Hydrobiologia* 311: 21-30.

Doll, B. 1997. Zebra Mussel Colonization: North Carolina's Risks. Pamphlet published by North Carolina Sea Grant, University of North Carolina, Raleigh, NC.

Ekman, S. 1953. Zoogeography of the Sea. Translated by E. Palmer. Sidgwick and Jackson, Ltd., London.

Elton, C.S. 1936. A new invader (review of Peters & Panning, 1933) *J. Anim. Ecol.* 5: 188-192.

Encyclopedia Britannica. 1994. The New Encyclopedia Britannica. Encyclopedia Britannica, Inc., Chicago.

Escaravage, V. and K. Soetaert. 1995. Secondary production of the brackish copepod communities and their contribution to the carbon fluxes in the Westerschelde estuary (The Netherlands). *Hydrobiologia* 311: 103-114.

Fuhrer, G.J., D.Q. Tanner, J.L. Morace, S.W. McKenzie and K.A. Skach. 1996. Water Quality of the Lower Columbia River Basin: Analysis of Current and Historical Water-Quality Data through 1994. Water-Resources Investigations Rept. 95-4294, U.S. Geological Survey, Portland, OR.

Gao, L. 2001. Response of the River Yangtze to dam construction. Fluvial Research Team Website, School of Geography, University of Nottingham, Nottingham, England. [http://www.geog.nottingham.ac.uk/newgeog/research/projects/fluvialgroup/index.htm#projects]

GEMS. 2001. GEMS - Laguna Madre Website. [http://www.tpwd.state.tx.us/texaswater/txgems/lagmadr/lagmadr.htm]

Gollasch, S. 1997. *Eriocheir sinensis*. In: Baltic Research Network on Ecology of Marine Invasions and Introductions, Olenin, S. and D. Daunys (eds.). [http://www.ku.lt/nemo/mainnemo.htm]

Gollasch, S. 1999. Current status on the increasing abundance of the Chinese Mitten Crab *Eriocheir sinensis* H. Milne Edwards, 1854 in German rivers. In: Proceedings of the First Annual Meeting on the Mitten Crab in California, Sacramento, CA, March 23, 1999.

Goosen, N.K., P. van Rijswijk, and U. Brockmann. 1995. Comparison of heterotrophic bacterial production rates in early spring in the turbid estuaries of the Scheldt and Elbe. *Hydrobiologia* 311: 31-42.

Grabda E., 1973. Krab welnistoszczypcy, *Eriocheir sinensis* Milne Edwards, 1853 w Polsce ["The crab *Eriocheir sinensis* Milne-Edwards, 1853 in Poland"]. *Przeglad Zoologiczny* 17(1): 46-49. [in Polish]

Gross, M.R., R.M. Coleman and R.M. McDowall. 1988. Aquatic productivity and the evolution of diadromous fish migration. *Science* 239: 1291-1293.

Guo, J.Y., N.K. Ng, A. Dai and P.K.L. Ng. 1997. The taxonomy of three commercially important species of mitten crabs of the genus *Eriocheir* de Haan, 1835 (Crustacea: Decapoda: Brachyura: Grapsidae). *Raffles Bull. Zool.* 45(2): 445-476.

Haahtela, I. 1963. Some new observations and remarks on the occurrence of the Mitten Crab, *Eriocheir sinensis* Milne-Edwards (Crustacea, Decapoda), in Finland. *Aquilo (Ser. Zool.)* 1: 9-16.

Halat, K.M. 1996. The Distribution and Abundance of the Chinese Mitten Crab (*Eriocheir sinensis*) in Southern San Francisco Bay, 1995-1996. M.S. thesis, University of California, Berkeley, CA.

Hamilton, P. 1990. Modelling salinity and circulation for the Columbia River Estuary, *Prog. Oceanogr.* 25: 113-156.

Hayward, D. and E. Estevez. 1997. Suitability of Florida Waters to Invasion by the Zebra Mussel, *Dreissena polymorpha*. Tech. Rept. No. 495, Florida Sea Grant College Program, Mote Marine Laboratory, Sarasota FL.

Hieb, K. 2001. San Francisco Bay fisheries monitoring. *Interagency Ecological Program Newsletter* (California Department of Water Resources, Sacramento, CA) 14(1): 5.

Hieb, K. and T. Veldhuizen. 1998. Mitten crabs on the move. *Interagency Ecological Program Newsletter* (California Department of Water Resources, Sacramento, CA) 11(2): 3-4.

Hincks, S.S, and G.L. Mackie. 1997. Effects of pH, calcium, alkalinity, hardness, and chlorophyll on the survival, growth, and reproductive success of zebra mussel (*Dreissena polymorpha*) in Ontario lakes. *Can. J. Fish. Aquat. Sci.* 54: 2049-2057.

Hoestland, H. 1948. Recherches sur la biologie de l'*Eriocheir sinensis* en France (Crustacé brachyoure) ["Investigations into the biology of *Eriocheir sinensis* in France (Crustacea: Brachyura)"]. *Ann. Inst. Océanogr., Monaco* 24(1): 1-116. [in French]

Hoestland, H. 1959. Répartition actuelle du crabe chinois (*Eriocheir sinensis* H. Milne Edwards) en France ["The current distribution of the Chinese mitten crab (*Eriocheir sinensis* H. Milne Edwards) in France"]. *Bull. Franc. Piscicult.* 194: 5-14. [in French]

Hydropower. 2001. China Hydropower Website. [http://www.china3gorges.com/HTML/Hydropower/EHYVL0708.htm]

Hymanson, Z., J. Wang and T. Sasaki. 1999. Lessons from the home of the Chinese Mitten Crab. *Interagency Ecological Program Newsletter* (California Department of Water Resources, Sacramento, CA) 12(3): 25-32.

Ingle, R.W. 1986. The Chinese Mitten Crab *Eriocheir sinensis* H. Milne Edwards - a contentious immigrant. *Lond. Naturalist* 65: 101-105.

Ingle, R.W. and M.J. Andrews. 1976. Chinese Mitten Crab reappears in Britain. *Nature* 263: 638.

Jazdzewski, K. and A. Konopacka. 1993. Survey and distribution of Crustacea Malacostraca in Poland. *Crustaceana* 65(2): 176-191.

Jin, G. and Z. Li. 1998. Characteristics of breeding migration of Chinese mitten crab (*Eriocheir sinensis*) from different water systems, reared in lakes at the middle reaches of Yangtse River (unpublished manuscript).

Josselyn. M.N. and J.A. West. 1985. The distribution and temporal dynamics of the estuarine macroalgal community of San Francisco Bay. *Hydrobiologia* 129: 139-152.

Kamps, L.F. 1937. Die chineesche Wolhandkrab in Nederland ["The Chinese Mitten Crab in the Netherlands"]. Dissertation, University of Groningen, The Netherlands. [in Dutch]

Kim, C.H. and S. G. Hwang. 1995. The complete larval development of the mitten crab *Eriocheir sinensis* H. Milne Edwards, 1853 (Decapoda, Brachura, Grapsidae) reared in the laboratory and a key to the known zoeae of the Varuninae. *Crustaceana* 68(7): 793-812.

Koutnik, M. and D.K. Padilla. 1994. Predicting the spatial distribution of *Dreissena polymorpha* (zebra mussel) among inland lakes of Wisconsin: modeling with a GIS. *Can. J. Fish. Aquat. Sci.* 51: 1189-1196.

Li, G., Q. Shen, and Z. Xu. 1993. Morphometric and biochemical genetic variation of the mitten crab, *Eriocheir*, in southern China. *Aquaculture* 111: 103-115.

McLaughlin, P.A. 1982. Comparative morphology of crustacean appendages. Pages 197-256 in: The Biology of Crustacea; Volume 2: Embryology, Morphology and Genetics, Aberle, L.G. (ed.), Academic Press, Orlando, FL.

McMichael, G.A., A.L. Fritts, T.N. Pearsons and J.L. Dunnigan. 1999. Lower Yakima River Predatory Fish Monitoring: Progress Report 1998. Washington Department of Fish and Wildlife, Olympia ,WA. [http://www.nwr.noaa.gov/nnative/proceed/mcmich.pdf]

Mees, J., N. Fockedey and O. Hamerlynck. 1995. Comparative study of the hyperbenthos of three European estuaries. *Hydrobiologia* 311: 153-174.

Middleburg, J.J., G. Klaver, J. Nieuwenhuize and R.M. Markusse. 1995. Nitrous oxide emissions from estuarine intertidal sediments. *Hydrobiologia* 311: 43-55.

Monroe, M.W. and J. Kelly. 1992. State of the Estuary. San Francisco Estuary Project, Oakland, CA.

Montú, M., Anger, K. and de Bakker, C., 1996. Larval development of the Chinese mitten crab *Eriocheir sinensis* H. Milne-Edwards (Decapoda: Grapsidae) reared in the laboratory. *Helgoländer Meeresunters.* 50: 223-252.

Morace, J.L., G.J. Fuhrer, J.F. Rinella, S.W. McKenzie and others. 1999. Surface Water Quality Assessment of the Yakima River Basin, Washington: Overview of Major Findings, 1987-1991. Water Resources Investigations Report 98-4113, U.S. Geological Survey, Portland, OR.

Moreira, F., C.A. Assis, P.R. Almeida, J.L. Costa and M.J. Costa. 1992. Trophic relationships in the community of the upper Tagus Estuary (Portugal): a preliminary approach. *Est. Coast. Shelf Sci.* 34: 617-623.

Murray, T.E., P.H. Rich and E.H. Jokinen. 1993. Invasion Potential of the Zebra Mussel *Dreissena polymorpha* (Pallas) in Connecticut: Predictions from Water Quality Data. Spec. Rept. No. 36., Connecticut Institute of Water Resources, University of Connecticut, Storrs, CT.

Neary, B.P. and J.H. Leach. 1992. Mapping the potential spread of the zebra mussel (*Dreissena polymorpha*) in Ontario. *Can. J. Fish. Aquat. Sci.* 49: 407-415.

Nepszy, S.J., and J.H. Leach. 1973. First records of the Chinese Mitten Crab, *Eriocheir sinensis*, (Crustacea: Brachyura) from North America. *J. Fish. Res. Bd. Can.* 30: 1909-1910.

Ng, K.L. 1988. The Freshwater Crabs of Peninsular Malaysia and Singapore. Shing Lee, Singapore.

Ng, N.K., A.Y. Dai, J. Guo and P.K.L. Ng. 1998. The complete larval development of the southern Chinese mitten crab *Eriocheir hepuensis* Dai, 1991 (Decapoda: Brachyura: Grapsidae) reared under laboratory conditions. *Crustaceana* 71(5): 493-517.

Ng, N.K., G. Junyao and P.K.L. Ng. 1999. Generic affinities of *Eriocheir leptognathus* and *E. formosa* with description of a new genus (Brachyura: Grapsidae: Varuninae). *J. Crust. Biol.* 19(1): 154-170.

NOAA 1997. Estuarine Eutrophication Survey Volume 4: Gulf of Mexico Region. National Oceanic and Atmospheric Administration, Office of Resources Conservation Assessment, Silver Spring, MD.

NOAA. 1998. Estuarine Eutrophication Survey Volume 5: Pacific Coast Region. National Oceanic and Atmospheric Administration, Office of Resources Conservation Assessment, Silver Spring, MD.

NOAA. 1999. Satellite Active Archive, 50 km Sea Surface Temperature Fields. National Oceanic and Atmospheric Administration, Silver Spring, MD. [http://las.saa.noaa.gov/las-bin/climate_server]

Noble, E.R., G.A. Noble, G.A. Schad and A.J. MacInnes 1989. The Biology of Animal Parasites (6th edition). Lea & Febinger, Philadelphia, PA.

NCRWQCB. 1969. Klamath River Bacteriological Investigation. North Coast Regional Water Quality Control Board.

ODFW. 1990. Tualatin River/Willamette River Subbasin Salmon and Steelhead Production Plan. Oregon Department of Fish and Wildlife, Portland OR. [http://www.streamnet.org/subbasin/Tualat.pdf]

O'Neill, C.R., Jr. 1996. The Zebra Mussel: Impacts and Control. Cornell Cooperative Extension Information Bull. No. 238, New York Sea Grant, Cornell University, Ithaca NY.

Page, G.L. 1973. The freshwater snails of Taiwan (Formosa). *Malacological Rev.* (Suppl. 1).

Panning, A. 1938. Systematisches über *Eriocheir sinensis* H. Milne-Edwards ["Systematic notes on *Eriocheir sinensis* H. Milne-Edwards"]. *Mitteilungen Hamburgischen Zool. Mus. Inst.* 47: 105-111. [in German]

Panning, A. 1939. The Chinese mitten crab. *Ann. Rep. Smithsonian Inst.* 1938: 361-375.

Panning, A. 1952. Die chinesische Wollhandkrabbe ["The Chinese mitten crab"]. *Die Neue Brehm-Bücherei (Akademische Verlagsgesellschaft, Leipzig)* 70: 1-46. [in German]

Parker, G. and J. Arnold. 1999. Mitten crab (*Eriocheir sinensis*) depletion of dissolved oxygen in a confined space. *Interagency Ecological Program Newsletter* (California Department of Water Resources, Sacramento, CA) 12(1): 9-10.

Peitsch, A. 1995. production rates of *Eurytemora affinis* in the Elbe estuary, comparison of field and enclosure production estimates. *Hydrobiologia* 311: 127-137.

Peters, N. 1933. Lebenskundlicher Teil ["Natural history section"]. Pages 59-156 in: Die Chinesische Wollhandkrabbe (*Eriocheir sinensis* H. Milne-Edwards) in Deutschland ["The Chinese Mitten Crab (*Eriocheir sinensis* H. Milne-Edwards) in Germany"], Peters, N. and A. Panning (eds.), Akademische Verlagsgesellschaft M.B.H., Leipzig. [in German]

Peters, N. 1938. Zur Fortpflanzungsbiologie der Wollhandkrabbe (*Eriocheir sinensis* Milne-Edwards) ["The reproductive biology of the mitten crab (*Eriocheir sinensis* Milne-Edwards"]. *Mitteilungen Hamburgischen Zool. Mus. Inst.* 47: 112-128. [in German]

Petit, G. 1960. Le "Crabe Chinois" est parvenu en Méditerranée ["The Chinese Crab arrives in the Mediterranean"]. *Vie Milieu* 11(1): 133-136. [in French]

Petit, G. and R. Mizoule. 1974. En douze ans le "Crabe chinois" na pu réussir son implantation dans les lagunes du Languedoc ["In twelve years the Chinese Crab did not become established in the Languedoc lagoons"]. *Vie Milieu* 23(1C): 181-186. [in French]

Prahl, F.G., L.F. Small, B.A. Sullivan, J. Cordell, C.A. Simenstad, B.C. Crump and J.A. Baross. 1998. Biogeochemical gradients in the lower Columbia river. *Hydrobiologia* 361: 37-52.

Ramcharan, C.W., D.K. Padilla and S.I. Dodson. 1992. Models to predict potential occurrence and density of the zebra mussel, *Dreissena polymorpha*. *Can. J. Fish. Aquat. Sci.* 49(12):2611-2620.

Rasmussen, E. 1987. Status over uldhåndskrabbens (*Eriocheir sinensis*) udbredelse og forekomst i Danmark ["Status of mitten crab (*Eriocheir sinensis*) outbreaks and occurrence in Denmark"]. *Flora og Fauna* 93(3): 51-58. [in Danish]

Ratti, F. 1979. Natural Resources of Rogue Estuary. Oregon Department of Fish and Wildlife, Research and Development Section, Portland, OR.

Risley, J.C. and M.C. Doyle. 1997. Water Temperature, Specific Conductance, and Meteorological Data for the Tualatin River Basin, Oregon, 1994-95. Open-File Rept. No. 96-315, U.S. Geological Survey, Portland, OR.

Rounds, S.A., T.M. Wood and D.D. Lynch. 1999. Modeling Discharge, Temperature and Water Quality in the Tualatin River, Oregon. Water Supply Paper 2465-B, U.S. Geological Survey, Portland, OR. [http://smig.usgs.gov/SMIG/features_0396/tual_w2.html]

Rudnick, D.A., V.H. Resh, and K.M. Halat. 1999. Economic and Ecological Impacts of the Chinese Mitten Crab (*Eriocheir sinensis*) in San Francisco Bay. Technical Completion Rept., Project No. UCAL-WRC-W-881, University of California Water Resources Center, Berkeley, CA.

Rudnick, D.A., K.M. Halat and V.H. Resh. 2000. Distribution, Ecology and Potential Impacts of the Chinese Mitten Crab (*Eriocheir sinensis*) in San Francisco Bay. Water resources Center Contribution #206, University of California Water Resources Center, Berkeley, CA.

Sakai, T. 1939. Studies on the Crabs of Japan. IV. Brachygnatha, Brachyrhyncha. Yokendo, Tokyo.

Sakai, T. 1976. Crabs of Japan and Adjacent Seas. Kodansha Ltd., Tokyo.

Sakai, T. 1983. Descriptions of new genera and species of Japanese crabs, together with systematically and biogeographically interesting species. *Res. Crust.* 12: 3-23.

Sautour, B. and J. Castel. 1995. Comparative spring distribution of zooplankton in three macrotidal European estuaries. *Hydrobiologia* 311: 139-151.

Sherwood, C.R., D.A. Jay, R.B. Harvey, P. Hamilton and C.A. Simenstad. 1990. Historical changes in the Columbia River Estuary. *Prog. Oceanog.* 25: 299-352.

Siegfried, S. 1999. notes on the invasion of the Chinese mitten crab (Eriocheir sinensis) and their entrainment at the Tracy fish collection facility. *Interagency Ecological Program Newsletter* (California Department of Water Resources, Sacramento, CA) 12(2): 24-25.

Silva, P.C. 1979. The benthic algal flora of central San Francisco Bay. Pages 287-345 in: San Francisco Bay: The Urbanized Estuary, Conomos, T.J., A.E. Leviton and M. Berson (eds.), Pacific Division of the American Association for the Advancement of Science, San Francisco.

Silversides Outfitters 1999. Rogue River water temperature 1940-1994. [http://www.silversides.com]

Simenstad, C.A., L.F. Small, C.D. McIntire, D.A. Jay and C. Sherwood. 1990. Columbia River estuary studies: an introduction to the estuary, a brief history, and prior studies. *Prog. Oceanog.* 25: 1-13.

Snider, W.M., D.B. Christophel, B.L. Jackson and P.M. Bratovich. 1992. Habitat Characterization of the Lower American River. California Department of Fish and Game, Sacramento, CA.

Soetaert, K., M. Vincx, J. Wittoek and M. Tulkens. 1995. Meiobenthic distribution and nematode community structure in five European estuaries. *Hydrobiologia* 311: 185-206.

Soetaert, K. and P.M.J. Herman. 1995. Estimating estuarine residence times in the Westerschelde (The Netherlands) using a box model with fixed dispersion coefficients. *Hydrobiologia* 311: 215-224.

Sorba, E.A. and D.A. Williamson. 1997. Zebra Mussel Colonization Potential in Manitoba, Canada. Manitoba Environment Report No. 97-07. Manitoba Environment, Manitoba, Canada.

STORET. 1999. Water quality database. U.S. Environmental Protection Agency, Region 9, San Francisco, CA.

Strandwerkgroep. 2001. Strandwoerkgroep Website. [http;//www.strandwerkgroep.org]

Strayer, D.L. 1991. Projected distribution of the zebra mussel, *Dreissena polymorpha*, in North America. *Can. J. Fish. Aquat. Sci.* 48: 1389-1395.

Sverdrup, H.U., M.W. Johnson and R.H. Fleming, 1942. The Oceans: Their Physics, Chemistry and General Biology. Prentice-Hall Inc., Englewood Cliffs, NJ.

Tesch, J.J. 1918. The Decapoda Brachyura of the Siboga Expedition. I. Hymenosomidae, Retroplumidae, Ocypodidae, Grapsidae and Gecarcinidae. *Siboga Monogr.* 39c.

Texas A&M. 2000. Texas Coastal Ocean Observation Network (TCOON). Texas A&M University, Corpus Christi, TX. [http://www.cbi.tamucc.edu/projects/tcoon/]

Texas SHA. 1999. The Handbook of Texas OnLine. The General Libraries at the University of Texas at Austin, and the Texas State Historical Association. [http://www.tsha.utexas.edu/handbook/online/index.new.html]

Texas WDB. 2001. Texas Bays and Estuaries Data Website. Texas Water Development Board, Austin, TX. [http://www.twdb.state.tx.us/data/bays_estuaries/bays_estuary_toc.htm]

Thiel, H. 1937. Die allgemeinen Ernährungsgrundlagen der chinesischen Wollhandkrabbe (*Eriocheir sinensis* Milne-Edwards) in Deutschland, insbesondere im Einwanderungsgebiet im weiteren Sinne ["The general nutritional basis for the Chinese mitten crab (*Eriocheir sinensis* Milne-Edwards) in Germany, specifically within its entire immigration range"]. *Mitteilungen Hamburgischen Zool. Mus. Inst.* 47: 50-64. [in German]

Tomczak, M. 2000. Shelf and Coastal Oceanography, Version 1.0. [http://www.es.flinders.edu.au/~mattom/ShelfCoast/notes/contents]

Tsukimura, B. and A. Toste. 2000. Reproduction in the Chinese mitten crab, *Eriocheir sinensis. Interagency Ecological Program Newsletter* (California Department of Water Resources, Sacramento, CA) 13(3): 13-16.

Tualatin Valley Watershed Council. 1999. Introduction to the Tualatin River. [http://www.trwc.org/]

University of Washington. 2001. Data Access in Real Time (DART). University of Washington, Columbia Basin Research Team, School of Fisheries, Seattle, WA. [http://www.cqs.washington.edu/index.html]

USACE. 1981. North Pacific Division Fish Facilities Manual. U.S. Army Corps of Engineers, Portland District, Fish and Wildlife Section, Portland, OR.

USACE. 1992. Willamette Falls Locks. U.S. GPO Publ. No. 1993-0-791-487, U.S. Army Corps of Engineers, Portland District, Portland, OR.

USACE. 1999. North Pacific Region Technical Management Team Website. U.S. Army Corps of Engineers, Northwest Division, Portland, OR. [http://www.nwd-wc.usace.army.mil/TMT/welcome.html]

USACE. 2001a. North Pacific Region:Water Management Data Website. U.S. Army Corps of Engineers, Northwestern Division, North Pacific Region Water Control Division, Portland, OR. [http://www.nwd-wc.usace.army.mil/report.htm#top]

USACE. 2001b. Columbia River Basin: Dams and Salmon Website. U.S. Army Corps of Engineers, Northwestern Division, Pacific Salmon Coordination Office, Portland, OR. [http://www.nwd-wc.usace.army.mil/ps/colbsnmap.htm]

USACE. 2001c. McNary Master Plan: Lake Wallula. U.S. Army Corps of Engineers, Walla Walla District, Walla Walla, WA. [http://www.nww.usace.army.mil/html/offices/pl/er/mcnary/mcnarymp.htm]

USBR. 1991. Lavaca-Navidad River Authority Pipeline Permit Final Environmental Assessment / Finding of No Significant Impact. U.S. Bureau of Reclamation, Great Plains Region.

USBR. 1998. Draft Report: Biologically Based Flows for the Yakima River Basin. U.S. Bureau of Reclamation, Pacific Northwest Division. [http://www.pn.usbr.gov/reg/was/soac/]

USBR. 2001. U.S. Bureau of Reclamation DataWeb: Project Data Reports. U.S. Bureau of Reclamation. [http://dataweb.usbr.gov/html/project_selection.html]

USDOE. 1995. Columbia River System Operation Review: Final Environmental Impact Statement: Appendix M: Water Quality. DOE/EIS-0170, U.S. Department of Energy, Bonneville Power Administration; U.S. Army Corps of Engineers, North Pacific Division; and U.S. Department of the Interior, Bureau of Reclamation.

USEPA. 1999. The Ecological Conditions of Estuaries in the Gulf of Mexico. Report no. EPA 620-R-98-004, National Helth and Environmenetal Effects Rsearch Laboratory, Office of Research and Development, U.S. Environmental Protection Agency, Washington, DC.

USEPA. 2001. Yakima River Basin Website. U.S. Environmental Protection Agency, Region 10, Seattle, WA. [http://yosemite.epa.gov/r10%5CECOCOMM.NSF/ecoweb/+Yakima+River+Basin+Menu]

USFWS. 1988. Proposed Rule: Injurious Wildlife: Mitten Crabs. *U. S. Federal Register* 53(219): 45784-45788 (Nov. 14, 1988).

USGS. 2000. Tualatin River Basin Water Quality Assessment. U.S. Geological Survey, Portland, OR. [http://or.water.usgs.gov/projs_dir/pn356/]

USGS. 2001. Watershed and River Systems Management Program-WARSMP: Application to the Yakima River Basin, Washington. U.S. Geological Survey. [http://wa.water.usgs.gov/warsmp/warsmp.html]

Veldhuizen, T. and K. Hieb. 1998. What's new on the mitten crabs front? *Interagency Ecological Program Newsletter* (California Department of Water Resources, Sacramento, CA) 11(3): 43.

Veldhuizen, T.C. and S. Stanish. 1999. Overview of the Life History, Distribution, Abundance, and Impacts of the Chinese Mitten Crab, *Eriocheir sinensis*. California Department of Water Resources, Environmental Services Office, Interagency Program, Sacramento, CA.

Veldhuizen, T. 2000. Predictions and predications from a visiting Chinese mitten crab expert *Interagency Ecological Program Newsletter* (California Department of Water Resources, Sacramento, CA) 13(1): 14-15.

Vincent, T. 1996. Le crabe Chinois *Eriocheir sinensis* H Milne-Edwards 1854 (Crustacea, Brachyura) en Seine-maritime, France ["The Chinese crab *Eriocheir sinensis* H Milne-Edwards 1854 (Crustacea, Brachyura) in coastal Seine, France"]. *Annales de l'Institut Oceanographic* 72(2): 155-171. [in French]

Wallace, M. 1998. Seasonal Water Quality Monitoring in the Klamath River Estuary, 1991-1994. Inland Fisheries Admin. Rept. No. 98-9, California Department of Fish and Game, Sacramento, CA.

Walter, M. and C. Culver. 2000. The Chinese mitten crab as a potential host for human parasitic lung flukes in the San Francisco Bay Estuary. *Interagency Ecological Program Newsletter* (California Department of Water Resources, Sacramento, CA) 13(3): 12-13.

Ward, G.H. and N.E. Armstrong. 1997. Ambient Water, Sediment and Tissue Quality of Corpus Christi Bay Study Area: Present Status and Historical Trends. CCBNEP Rep. no. 13, Corpus Christi Bay National Estuary Program. [http://tarpon.tamucc.edu/library/FinalReports/pdf/EX13.html]

Weinstein, A. and A.N. Cohen. 2001. Geographic risk assessment for exotic species based on the environmental threshold model: Estimating zebra mussel's potential distribution in California. (in prep.).

WESCO. 1988. Marine Resources Survey of Central San Francisco Bay. Report for U.S. Army Corps of Engineers, San Francisco District, San Francisco, CA, by Western Ecological Services Company, Inc., Novato, CA.

Wolff, W. J. and J.J. Sandee. 1971. Distribution and ecology of the Decapoda Reptantia of the estuarine area of the rivers Rhine, Meuse and Scheldt. *Neth. J. Sea Res.* 5: 197-226.

Wynn, S., B. Bridges, L. Hess, S. Siegfried and C. Liston. 1999a. The Invasion of the Chinese Mitten Crab and Effects on Fish Protection Facilities [fact sheet]. U.S. Bureau of Reclamation.

Wynn, S., L. Hess, C. Liston and M. Haegele. 1999b. The invasion of the Chinese mitten crab and its effects on fish protection facilities. Selected abstracts from the Ninth International Zebra Mussel and Aquatic Nuisance Species Conferenmce, April 28-30, 1999, Duluth MN. *Dreiaaena!* 10(4): 5-6.

Xie, G. 1996. ["Studies on the relationship of three kinds of mitten crabs using RAPD technique"]. M. Sc. thesis, Institute of Hydrobiology, Academia Sinica, Wuhan, China. [in Chinese]

Yu, M., M. Li and C. Liang. 1988. The ecology of economic shellfishes and their resources in Dapeng Bay. Pages 113-120 in: Proceedings on Marine Biology of the South China Seas, Xu. G. and B. Morton (eds.), China Ocean Press, Beijing.

Zimmermann, C., A. Matheja and O. Stoschek. 2000. Reduction of Harbor Sedimentation at a Tidal River. Franzius-Institut for Hydraulic, Waterways and Coastal Engineering, University of Hannover, Germany. [http://www.fi.uni-hannover.de/~am/pce2000/pce2000.html]

Presentations

Hymanson, Z. 1999. The Chinese mitten crab in its native range. Presentation at a Mitten Crab Project Work Team (Interagency Ecological Program) meeting, Stockton, CA, July 1, 1999.

Zhao, N. 1999. Presentation at a Mitten Crab Project Work Team (Interagency Ecological Program) meeting at the San Francisco Estuary Institute, Richmond, CA, August 26, 1999.

Personal Communications

Anger, Klaus von. Biologische Anstalt Helgoland, Alfred Wegener Institute für Polar- und Meeresforschung, Helgoland, Germany

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Buettner, Mark. U.S. Bureau of Reclamation, Mid-Pacfic Region, Klamath Falls, OR.

Confer, Todd. Oregon Department of Fish and Wildlife, Portland, OR (unpublished data from Oregon Department of Fish and Wildlife for 1975-77).

Crivelli, A. J. Tour du Valat Station Biologique, Le Sambuc, France.

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Noel, Pierre. Muséum National d'Histoire Naturelle, Paris, France.

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Zhang, Lie-Shi. Shanghai Fisheries Research Institute, Shanghai, China (personal communication to Johnson Wang, U.S. Bureau of Reclamation, Tracy Fish Collection Facility, Tracy, CA), translated by Johnson Wang.

Zhao, Nai-Gang. Anhui Weiqing Aquatic Products Company, Ltd., Shanghai, China (interview by A.N. Cohen on August 17, 1999, with translation by Johnson Wang).